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INTERNATIONAL
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AEROSPACE RECOMMENDED PRACTICE

SAE ARP4260

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Submitted for recognition as an American National Standard

Photometric and Colorimetric Measurement Procedures for Airborne Flat Panel Displays

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1. SCOPE:

This SAE Aerospace Recommended Practice (ARP) contains methods used to measure the optical performance of airborne flat panel display (FPD) systems. The methods described are specific to the direct view, liquid crystal matrix (x-y addressable) display technology used on aircraft flight decks. The focus of this document is on active matrix, liquid crystal displays (LCD), however, the majority of the procedures can be applied to other display technologies.

The document covers monochrome and color LCD operation in the transmissive mode within the visual spectrum (the wavelength range of 380 to 780 nm). These procedures are adaptable to reflective and transflective displays paying special attention to the source illumination geometry.

Generally, the procedures describe manual single point measurements. The individual procedures may be readily incorporated into automated testing equipment (ATE) or other automated environments. This also includes, but is not limited to Fourier scopes and video imaging devices.

1.1 Purpose:

This document is intended as a guide toward standard measurement practices in support of ARP4256 but is not limited to its requirements. The use of this document is not as a basis for legal regulation.

1.2 Field of Application:

This document defines three classes of tests. Each class of test is applicable to the different phases of a product's life [e.g., engineering development (Class 1), production/quality assurance (Class 2), and service/flight readiness (Class 3)]. The test requirements for each of these phases differ and hence the test procedures for each test class may differ. Each procedure in this document is Class 1 unless otherwise stated.

1.3 Classes of Tests:

Class 1 - Laboratory Tests - The objective of tests in this class is to verify the design of the display system. Tests in this class are most appropriate in an engineering laboratory environment or as part of a certification program.

Class 2 - Production/Quality Assurance - The objective of this test class is to verify that every display has been manufactured or repaired to meet specified requirements. Tests in this class are most appropriate for acceptance and/or end item tests.

Class 3 - Maintenance/Flight Readiness - The objective of tests in this class is to verify that display performance is within acceptable flight limits. Tests in this class are most appropriate for field service and flight line inspection.

1.3.1 Categories of Test: The test procedures of this document are divided into three categories:

Photometric: Luminance and Chromaticity
Geometric: Spatial Measurements
Temporal: Time-Based Measurements

1.3.2 Procedure Constraints: The test procedures of this document are designed to be performed under the following constraint: no internal access to the unit under test is allowed for Class 2 and Class 3 testing.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AMS 2521B	Reflection Reducing Coatings for Instrument Glass
ARP1874	Design Objectives for Electronic Displays for Transport Aircraft
ARP1782	Photometric and Colorimetric Measurement Procedures for Airborne Direct View CRT Displays
ARP4067	Design Objectives for Electronic Displays for Part 23 Aircraft
ARP4101	Flight Deck Layout and Facilities
ARP4256	Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft
AS8034	Minimum Performance Standard for Airborne Multipurpose Electronic Displays
J1330	Photometric Lab Accuracy Guidelines

2.1.2 ASTM Publications: Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM E 308	Measurement of Color
ASTM E 1455	Obtaining Colorimetric Data From a Visual Display Unit Using Tristimulus Colorimeters

2.1.3 CIE Publications: Available from TLA Lighting Consultants, 7 Pond St., Salem, MA 01970.

Pub. S001	Colorimetric Illuminants
Pub. S002	Colorimetric Observers
Pub. 15	Colorimetry, Supplement 2nd
Pub. 17.4	International Lighting Vocabulary, 4th Edition
Pub. 18.2	The Basis of Physical Photometry
Pub. 53	Methods of Characterizing the Performance of Radiometers and Photometers
Pub. 63	The Spectroradiometric Measurement of Light Sources
Pub. 64	Determination of the Spectral Responsivity of Optical Radiation Detectors
Pub. 69	Methods of Characterizing Illuminance Meters and Luminance Meters

2.1.4 EIA Publications: Available from EIA Engineering Department - Standard Sale Office, 2500 Wilson Boulevard, Arlington, VA.

EIA PUB #31-A and 31 (Color)

2.1.5 EIAJ Publications: Available from Electronic Industries Association, Japan, 250 West 34 St., Suite 1533, New York, NY 10119.

JIS C 7071-198	General Rule of Liquid Crystal Display Panel (draft, in Japanese)
JIS C 7072-198	Measuring Methods for Liquid Crystal Display Panels (draft, in Japanese)
LD-101-1980	Terms and Definitions for Liquid Crystal Display Devices
LD-201-1984	Measuring Methods for Liquid Crystal Display Panels and Constructive Materials

The JIS (Japan Industry Standard) publications referenced in 2.1.5 of ARP4260 are obtainable from ANSI, however, the EIAJ appears to have similar documents albeit with different document numbers.

The LD prefixed documents come from the EIAJ Liquid Crystal Committee and are not standards.

2.1.6 U.S. Government Publications: Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-STD-1787B	Aircraft Display Symbology
MIL-P-7788F	Panels, Information, Integrally Illuminated
MIL-HDBK-87213	Electronically/Optically Generated Airborne Displays

2.2 Related Publications:

The following publications are provided for information purpose only and are not a required part of this document.

Naval Air Development Center Report 86011-60 (AD-A168 563) The Development and Evaluation of Color Systems for Airborne Applications: Fundamental Visual, Perceptual and Display Systems Considerations, R. M. Merrifield, L. D. Silverstein, February, 1986.

NOTE: The above report is identical to the report (DOT/FAA/PM-85/19) of the same title published by the U.S. Department of Transportation and the Naval Air Test Center on July 18, 1985.

American National Standard for Human Factors Engineering of Visual Display Terminal Work Stations: Revised Draft, July 1986.

Billmeyer, F. W. Jr. and Saltzman, M.: Principles of Color Technology, 2nd Ed., 1981, John Wiley and Sons, N.Y.

Carter, R. C., Carter, E. C.: "High-Contrast Sets of Colors", Applied Optics, Vol. 21, No. 16, pp. 2936, 15 August 1982.

Grum, F. and Bartleson, C. J., Optical Radiation Measurements, Vol. 2, 1980, Academic Press, N.Y.

Silverstein, L. D., Lepkowski, J. S., Carter, R. C. and Carter, E. C.: Modeling of Display Color Parameters and Algorithmic Color Selection, Proceedings of the International Society for Optical Engineering, Vol. 624, 1986.

Stimson, A., Photometry and Radiometry for Engineers, 1974, John Wiley and Sons, N.Y.

Wyszecki, G. and Stiles, W., Color Science, 2nd Ed., 1982, John Wiley and Sons, N.Y.

Kaufman, John E (Ed), IES Lighting Handbook, 1981, Illuminating Engineering Society of North America, N.Y.

2.3 Definitions:

See Appendix A.

2.4 Terminology and Abbreviations:

AMLCD	Active Matrix Liquid Crystal Display
ARP	Aerospace Recommended Practice
ASTM	American Society of Testing and Materials
CIE	Commission International De E'clairage
CR	Contrast Ratio
DEP	Design Eye Position
DERP	Design Eye Reference Point
DVE	Design Viewing Envelope
EIA	Electronic Industry Association
EIAJ	Electronic Industry Association Japan
FOV	Field of View
FPD	Flat Panel Display
IES	Illumination Engineering Society
LCD	Liquid Crystal Display
NIST	National Institute of Standards and Technology
SAE	Society of Automotive Engineers
UUT	Unit Under Test

3. GENERAL REQUIREMENTS:

3.1 Units of Measure:

3.1.1 Linear Measurement Units: The units of linear measurement used in this procedure are as follows:

TABLE 1

Unit of Measurement	Abbreviation
millimeter	mm
nanometer	nm
inch	in
Thousandths of an inch	mil

These units are related by the following equations:

$$1 \text{ in} = 25.4 \text{ mm} \quad \text{(Eq. 1)}$$

$$1 \text{ nm} = 1 \times 10^{-9} \text{ meters} \quad \text{(Eq. 2)}$$

$$1 \text{ mm} = 0.03937 \text{ inches} \quad \text{(Eq. 3)}$$

$$1 \text{ mil} = 0.0254 \text{ mm} \quad \text{(Eq. 4)}$$

3.1.2 Luminance Units: Luminance is a measure of luminous intensity per unit area. The units of luminance used in this document are either the footlambert (fL) or candela per square meter (cd/m^2). To convert from footlamberts to candelas per square meter(cd/m^2), multiply the number of footlamberts by 3.426.

$$1 \text{ fL} = 3.426 \text{ cd/m}^2 \quad \text{(Eq. 5)}$$

To convert from candelas per square meter to footlamberts, multiply the number of candelas per square meter by 0.2919.

$$1 \text{ cd/m}^2 = 0.2919 \text{ fL} \quad \text{(Eq. 6)}$$

3.1.3 Illuminance Units: Illuminance is the metric for the measurement of light from a source that is incident on a surface. The units of illuminance used in this document are the footcandle ($lumen/ft^2$) and the lux ($lumen/m^2$).

To convert from footcandles (fc) to lux, multiply the number of footcandles by 10.76. Similarly, to convert from lux to footcandles, multiply the number of lux by 0.0929.

$$1 \text{ fc} = 10.76 \text{ lux} \quad \text{(Eq. 7)}$$

$$1 \text{ lux} = 0.0929 \text{ fc} \quad \text{(Eq. 8)}$$

3.2 Laboratory Conditions:

The following conditions shall be adhered to when measuring displays in this document.

3.2.1 Temperature: Measurements shall be conducted within an ambient air temperature range of 18 to 25 °C. All equipment and the UUT should be stabilized to the ambient temperature.

3.2.2 Humidity: Measurements shall be conducted within a relative humidity range of 15 to 60%.

3.2.3 Electrical Input Power: The primary, electrical input power (AC or DC) to the UUT shall be controlled to within ±1% in voltage and frequency.

3.2.4 Ambient Light: Ambient light is considered to be all light incident on the display surface from sources other than the display itself.

Measurement procedures in this document shall be conducted under dark ambient conditions, unless otherwise specified, such that the incident light at the plane of the display surface is less than 1% of the level of the display. The ambient light level should be determined prior to any display measurements.

3.3 Laboratory Standards:

The use of industry traceable (e.g., NIST) radiometric and photometric standards for the calibration of test equipment will help ensure inter-instrument correlation. Some standards are required to be recalibrated on a regular cycle or when an elapsed time of use has expired. Strict adherence to calibration and recalibration and maintaining calibration records is prerequisite to good laboratory procedure and is highly recommended.

3.3.1 Radiance Standard: The primary standard for calibration of light measuring equipment is the spectral radiance standard. It is used to calibrate the spectral response of spectroradiometers. A radiance standard is generally an incandescent lamp and a light diffusing surface (transmitting or reflecting) operating in combination at or near a color temperature of 2856 K. A typical spectrum is shown in Figure 1.

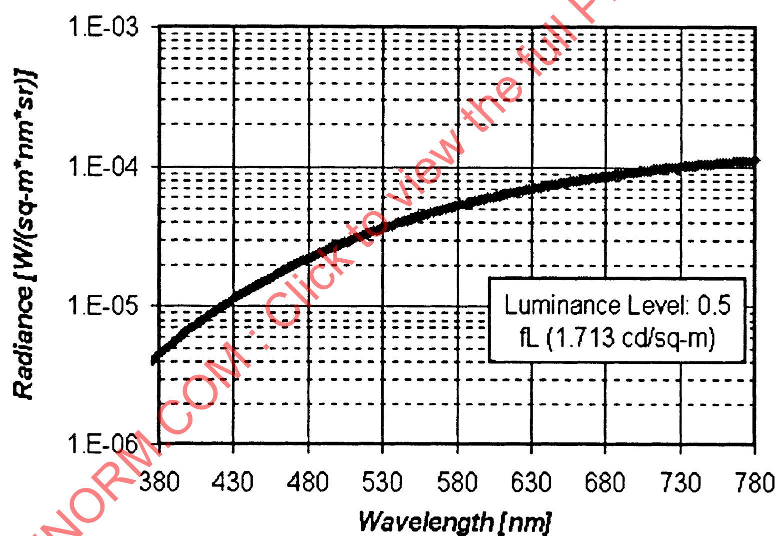

FIGURE 1 - Spectral Distribution of Radiance Standard

The lamp is selected for its continuous spectrum, stable output, drive simplicity, and general long life. The radiance data supplied with the lamp is in units of watts per square meter and nanometer and steradian and given in 1, 2, or 5 nanometer steps for a specified lamp current. Typical standards are configured as lamp with reflectance standard, lamp with diffusing transmittance standard, and lamp with integrating sphere. The diffuse surface must exhibit lambertian characteristics (see 3.3.4.1).

3.3.2 Luminance Standard: The luminance standard is used to calibrate photometers. This standard is generally similar to the radiance standard with the exception (or addition) that the integrated luminance is supplied with the lamp. The luminance standard supplies a certified luminance (fixed or adjustable) at a specified color temperature.

3.3.3 Illuminance and Irradiance Standards: These standards are generally not necessary. When a particular illuminance, color temperature, or irradiance is required for measuring reflectance and contrast, a lamp (quartz-halogen lamp or xenon arc lamp) is calibrated by measuring the reflected luminance from a diffuse reflectance standard.

3.3.4 Reflectance Standards:

3.3.4.1 Diffuse Reflectance: A diffuse reflectance standard is one that reflects, spectrally non-selectively, incident radiation into a lambertian distribution. In the past, most reflectance standards and targets have been made of compressed barium sulfate, $BaSO_4$, but recently available polytetrafluoroethylene materials exhibit very similar response with the added benefits that they are durable and can be cleaned. The $BaSO_4$ block is a powder compressed to form a white diffuse surface.

"A Lambertian source is a surface source that manifests luminous intensity in any direction proportional to the cosine of the angle between that direction and the normal to the surface at the point in question. An illuminated Lambertian surface would reflect perfectly diffused light. Its luminance would be independent of the direction from which it is observed." - Photometry and Radiometry for Engineers, Allen Stimson.

There are no ideal lambertian surfaces but the materials described above approximate them very well. For the special case of a perfect Lambertian reflector, illuminance of 1 fc results in a surface luminance of 1 fL (illumination of 1 lux results in a luminance of $1/\pi$ cd/m^2 in the metric system). In a typical setup, this special case relationship between illuminance and luminance allows measurement of the illuminance at the display face without moving the photometer or changing detectors. One simply locates a near-Lambertian reflector in place of the display face, measures the luminance of the reflector, and multiplies this by its reflectance of approximately 1.0 (and by $1/\pi$ if metric units are used) to obtain the luminance.

3.3.4.2 Specular Reflectance: A purely specular surface is likened to a front surface mirror. The reflected light leaving the mirror's surface is at the same angle but on the opposite side of the normal to that surface.

A silver-coated, front surface mirror would seem the obvious choice for a specular reflectance standard. However, the best protective coatings are hard to clean without scratching and short lived due to wear and aging (oxidation). The reflectance of a coated surface is wavelength and incident angle dependent which makes calibration of the mirror difficult and requires frequent recalibration.

Certain types of glass (e.g., BK-7 from Schott Glass Works) can be used as specular reflectance standards and have been used as such especially for low level reflectance standards because their dispersion properties are constant between melts. The reflectance from this glass is computed for a single incident angle using the index of refraction with Snell's law (Equation 9) and the Fresnel reflection/refraction equation (Equation 10).

$$n_i \sin\theta_i = n_r \sin\theta_r \qquad \text{(Eq. 9)}$$

$$R_i = \tfrac{1}{2}\left[\frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} + \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)}\right] \qquad \text{(Eq. 10)}$$

where:

θ_i = incident angle
θ_r = refracted angle

and where

n_i = index of refraction in the incident medium
n_r = index of refraction in the refracted medium
R_i = reflectance at the interface of the incident and refracted media

The Sellmeier dispersion formula, shown in Equation 11 and whose coefficients (A_0, A_1, etc.) are published by the glass supplier, is used to compute the indices of refraction for the visible range. The index of refraction for air is a constant (n_0 = 1.003). The refracted angle, θ_1, is determined from Snell's Law and inserted into the Fresnel equation, θ_r.

$$n^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8} \qquad \text{(Eq. 11)}$$

3.3.4.2 (Continued):

Specular reflectance of a standard is given for a specific light source and angle. Knowing the spectral distribution of the light source, S_l, the reflectance is found by the following equation.

$$R = \frac{\sum_{380\ nm}^{780\ nm} S_\lambda R_\lambda \bar{y}_\lambda \Delta\lambda}{\sum_{380\ nm}^{780\ nm} S_\lambda \bar{y}_\lambda \Delta\lambda} \qquad \text{(Eq. 12)}$$

where:

$\Delta\lambda$ = wavelength interval
R_λ = spectral reflectance
$\bar{y}_\lambda$ = CIE standard (photopic) observer function

3.3.5 Wavelength Calibration Standards: Spectroradiometers operate by breaking up the input light into packets or bands of light and for a spectroradiometer to measure light accurately, it must determine the location of UUT's spectral peaks and the distribution. To do this, they must be calibrated for wavelength accuracy. Wavelength calibration standards are used to check and or calibrate the wavelength accuracy and repeatability of spectroradiometers. Line spectra sources and absorption filters are two types that have been used for this purpose. Line spectra emission sources are recommended over absorption filters.

3.3.5.1 Line Spectra: When gaseous elements are ionized they emit a signature of light at specific wavelengths that is dependent on the atomic structure of the gas. These signatures are invariant to temperature or pressure and are extremely accurate spectral lines for calibration. The line spectra are emitted from small low pressure arc lamps. Mercury, mercury/cadmium, helium, and helium/argon lamps are examples of sources that provide several spectral lines in the visible spectral range.

3.3.5.2 Absorption Filters: Certain types of glass exhibit multiple absorption bands which are stable, narrow, and deep. These glasses are suitable for wavelength calibration.

3.4 Measurement Equipment:

3.4.1 Measuring Optics: The measuring aperture should be centrally positioned in the area to be measured. Referring to Figure 2 which shows typical examples of measuring apertures and areas, the dimension D_1 should be between 50 to 80% of dimension D_2. The measuring field of the luminance meter or colorimeter should be more than or equal to one degree of subtended arc but not more than 10°.

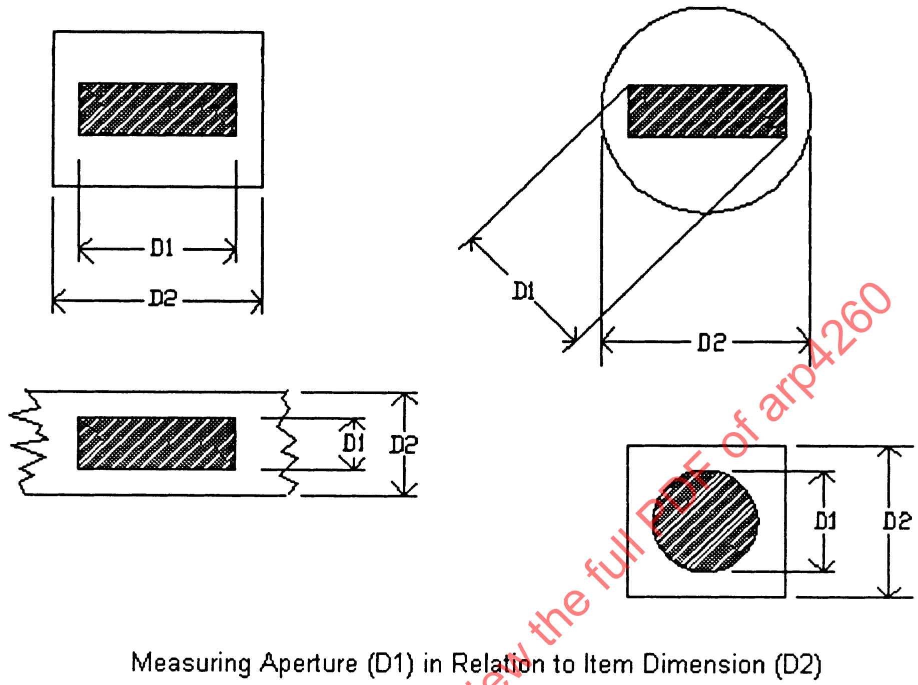

FIGURE 2 - Measurement Optics

3.4.2 Luminance: For luminance measurements, a calibrated spot photometer meeting the requirements of the document is the instrument of choice. The photometer shall have a polarization-free optical system, and should feature a viewing system in which the measuring aperture and alignment aperture are one and the same, especially for critical alignment on small objects. The spot photometer is specified over the spectroradiometer for luminance measurements because of its generally superior sensitivity, dynamic range and near real time measurement capability. In some cases (e.g., fluorescent light source), it may be necessary to first correlate the luminance of the photometer to an initial spectoradiometer measurement due to a possible mismatch of the photometer's photopic filter in critical spectral regions.

3.4.2.1 Spot Photometer: An instrument used to measure luminance (brightness) of an object is called a photometer. The IES defines the photometer as "a device for measuring radiant energy in the optical (UV, visible, Near-IR) spectrum. When used with a filter to correct their response to the C.I.E. standard observer, they measure visible light and are called physical photometers." The incoming signal is collected by means of a lens (e.g., telescopic or microscopic) and imaged on a measuring aperture, usually circular. The signal is then passed through a filter to a detector (usually a photomultiplier or silicon photodiode). The filter/detector combination is fitted to achieved the CIE 2° Standard Observer function. The viewed image, including the alignment aperture (or reticle) and immediate surrounding area, is observed through viewing optics. Ideally, the measuring aperture and alignment aperture are the same.

3.4.2.1.1 Photometer Sensitivity: The most sensitive full-scale range shall be 0.1 fL or less.

3.4.2.1.2 Photometer Accuracy: A calibrated photometer's measured luminance of a standard shall be within ±2% of the standard's certified value. The accuracy or a calibrated photometer shall be ±4% when measuring a non-standard luminance source.

3.4.2.1.3 Photometer Sensitivity and Accuracy Verification:

3.4.2.1.3.1 Scope: This test will verify the full-scale sensitivity and measurement accuracy of a spot photometer.

3.4.2.1.3.2 Equipment:

1. Certified luminance standard capable of providing 0.1 fL or less.
2. Spot photometer under test.

3.4.2.1.3.3 Setup:

1. Turn on the luminance standard and the photometer under test: allow sufficient warm-up time.
2. Adjust the standard to 0.1 fL (or less).
3. Align and focus the photometer on the standard's measuring plane.

3.4.2.1.3.4 Procedure:

1. Measure the standard's luminance with the spot photometer and note the reading.
2. The spot photometer shall have passed this verification if the measured reading is within ±2% of the stated output of the luminance standard.

3.4.2.1.4 Readout Resolution: The photometer should have a digital readout with a resolution better than or equal to 0.1% of full scale (3-1/2 digits).

3.4.2.1.5 Alignment System: The indicated measurement area as viewed through the photometer's optics or eye-piece shall be within 5% of the dimensions of the area being covered in both x and y axes. This is especially important for applications where the largest dimension of the measuring aperture is 80% of the smallest dimension of the sample.

3.4.2.1.6 Alignment System Verification:

3.4.2.1.6.1 Scope: This test is required for photometers whose measuring aperture and alignment aperture are not the same, that is, for photometers that rely on an alignment reticle for positioning of the system's measuring aperture.

3.4.2.1.6.2 Equipment:

1. Spot photometer under test.
2. Black card with a hole in the center.
3. Uniform light source (e.g., luminance or radiance standard) with lighted surface luminance uniformity of ±1%.
4. Two-axis positioner with gradation.

3.4.2.1.6.3 Setup:

1. Place the black card in front of the light source normal to the photometer's optical path.
2. Select a measuring aperture whose largest dimension (if not circular) is less than or equal to 80% of the diameter of the hole.
3. Align the aperture such that a small movement of the card in any direction does not cause a noticeable change in the luminance (less than ±1%).

3.4.2.1.6.4 Procedure:

1. Move the card in the horizontal axis with relation to the photometer's optical axis until a luminance decrease of 1.5% is observed on the photometer's output display.
2. Record the horizontal position of the card (P_1).
3. Move the card in the opposite direction and in the same axis as the original movement, until a 1.5% decrease in luminance is observed.
4. Record the position of the card P_2.
5. Calculate the distance (D) the card was moved: $D = |P_1 - P_2|$.
6. Move the card in the original direction by the distance D/2.
7. Repeat the above setup and procedure for the vertical axis (axis orthogonal to the horizontal test).
8. Replace the measuring aperture with the alignment reticle.
9. If the center of the reticle crosshair is not visually centered in either axis of the hole in the card, move the card until the center of the reticle is visually centered.
10. Record the distance and direction the card was moved in both axes.
11. If the distance (D_{horiz} and D_{vert}) the card was moved to achieve visual centering is greater than 5% of the calculated dimension of the measuring aperture as subtended at the plane of the hole, the alignment system is inadequate.
12. If the alignment system fails the verification test, do either: (1) recalibrate the alignment system or (2) when aligning the optical system on the UUT, compensate the position of the alignment by D_{horiz} and D_{vert} in the required direction.

3.4.2.1.7 Polarization Error: The polarization error of the photometer shall be no greater than 5%. This test can be used with spectroradiometers as well.

3.4.2.1.8 Polarization Error Verification:

3.4.2.1.8.1 Scope: This verification procedure will determine the polarization error of the spot photometer.

3.4.2.1.8.2 Equipment:

1. Spot photometer under test.
2. Uniform and diffuse light source.
3. Highly efficient, linear polarizer with rotator graduated in 5° increments minimum.

3.4.2.1.8.3 Setup:

1. Warm up the photometer and light source.
2. Align the photometer normal to the light source so that a luminance value may be recorded.
3. Place the polarizer in the optical path between the source and the photometer such that the axis of polarization is horizontal. The rotation axis of the polarizer should be aligned with the optical axis of the photometer.

3.4.2.1.8.4 Procedure:

1. Record the luminance through the polarizer, $L_{0°}$.
2. Rotate the polarizer by 45° and re-measure the luminance, $L_{45°}$.
3. Repeat step 2 until readings of $L_{0°}$ through $L_{135°}$ are obtained.
4. Calculate the percentage difference between the highest and lowest values of luminance.

$$\%L_{difference} = \frac{(L_{highest} - L_{lowest})}{L_{highest}} \times 100 \qquad \text{(Eq. 13)}$$

5. If the difference is greater than 5%, the photometer should not be used in these procedures.

3.4.2.1.9 Photodetector Saturation: The photometer's photodetector must not saturate over the usable luminance range of the UUT. This phenomenon occurs especially in photometers using photomultiplier tubes as detectors.

3.4.2.1.10 Photodetector Saturation Verification:

3.4.2.1.10.1 Scope: This verification procedure will determine if the photodetector is saturating.

3.4.2.1.10.2 Equipment:

1. Calibrated photometer.
2. Neutral density filters unless built into the photometer.
3. UUT

3.4.2.1.10.3 Setup:

1. The photometer and display are assumed to be on and warmed up.
2. Focus the calibrated photometer on the display.
3. Using the desired measuring aperture, select the lowest range of amplification and attenuation, to obtain a reading.

3.4.2.1.10.4 Procedure:

1. Record the initial reading from the photometer.
2. Add a neutral density filter (one decade of attenuation).
3. Record this second reading and divide by the initial reading. The photometer response should change in proportion to the calculated attenuation of the optical filters.
4. If the response does change proportionally, then photodetector saturation has not occurred and the first neutral density filter can be removed.
5. If the ratio is not proportional then add a second decade of neutral density, record this third reading, and divide this reading by the previous reading.
6. If saturation occurs, the system sensitivity should then be adjusted either electrically or optically (using neutral density filters) until the response change is proportional. This adjustment may require recalibration of the photometer.

3.4.2.1.11 Spectrally Induced Luminance Errors: Spectrally induced errors should not substantially contribute to the measurement errors of luminance (e.g., by not more than a 2%).

3.4.2.1.12 Spectrally Induced Luminance Error; Correction Factor Derivation:

3.4.2.1.12.1 Scope: This procedure will determine luminance correction factors, K_L, for errors caused by a significant mismatch between the CIE Standard Observer (V_λ) and the photopic response of the photometer.

3.4.2.1.1.2 Equipment:

1. Spot photometer
2. Spectroradiometer (see 3.4.1.2)
3. UUT

3.4.2.1.12.3 Setup:

1. The display and test equipment are assumed to be on and warmed up.
2. Locate and mark a position on the display so that the spectroradiometer may be re-focused onto the same point.

3.4.2.1.12.4 Procedure:

1. Command the UUT to display the desired color.
2. Align and focus the photometer on the area to be measured.
3. Measure the luminance with the photometer and record the reading as L_P.
4. Select a measuring aperture and lens combination on the spectroradiometer that provides the same shape and measuring spot size as used by the photometer in step 2.
5. Using the measuring aperture selected in step 4, align and focus the spectroradiometer on the exact area measured by the photometer in step 3.
6. Measure the UUT with the spectroradiometer and record the reading as L_S.
7. Compute luminance correction factors by dividing the spectroradiometer's luminance reading by the photometer's luminance reading for the same color.
8. Repeat this procedure for all colors of interest.

$$K_L = \frac{L_S}{L_P} \quad \text{(Eq. 14)}$$

9. To apply the correction factors, multiply the photometer's luminance reading by the color correction factor.

$$L = K_L \times \text{Photopic Reading} \quad \text{(Eq. 15)}$$

3.4.2.2 Spot Spectroradiometer: A spot spectroradiometer measures the spectral radiant distribution of light of an area of interest by imaging the area onto the spectroradiometer's measurement aperture. The signal passes through the aperture and is then diffracted onto the detector. There are two types of spot spectroradiometer typically used for display measurements: the scanning monochromator and simultaneous acquisition type. Scanning monochromators employ a single detector to measure the incoming spectrum in discrete wavelength steps while the simultaneous models sample the entire spectrum across multiple detectors in a single measurement.

The measured spectral data is corrected to spectral radiance and then luminance (see Equation 16). See 3.4.2.1 for spectral radiance verification and calibration of the spot spectroradiometer.

$$L_v = K_m \bullet \sum_{380}^{780} (L_e(\lambda) \bullet V(\lambda)) \bullet \Delta\lambda \quad \text{(Eq. 16)}$$

3.4.2.2 (Continued):

where:

K_m = maximum luminous efficacy (683 lm·W^{-1})

$L_e(\lambda)$ = spectral radiance $\left[\frac{W}{m^2 \cdot sr \cdot nm}\right]$

$V(\lambda)$ = CIE Standard Observer

$\Delta\lambda$ = Wavelength Interval

L_v = Luminance $[cd/m^2]$ since cd = lm · sr^{-1}

Computers are used to control the spectroradiometer's hardware, calibrate the system, collect the data, and make this computation.

The same restrictions that apply to the spot photometer (alignment, polarization error, and saturation) also apply to the spot spectroradiometer.

3.4.3 Color: The equipment selection hierarchy for color measurement is a spectroradiometer first and a filter colorimeter second. Color matching is not a valid technique for this document. Use the colorimeter when the radiance levels are not sufficient for the spectroradiometer or if polarized light affects spectroradiometer measurements (see 3.4.2.1.8). The document, ASTM E 1455, describes a procedure to correlate data between a colorimeter and a spectroradiometer.

3.4.3.1 Spot Spectroradiometer: The chromaticity of an object is computed from its tristimulus values which are in turn computed from the spectral radiance and the CIE color matching functions shown in the following equations.

Tristimulus Values (X, Y, Z):

$$X = K_m \cdot \sum_{380}^{780} (R(\lambda) \cdot \bar{x}(\lambda))\Delta\lambda \qquad \text{(Eq. 17)}$$

$$Y = K_m \cdot \sum_{380}^{780} (R(\lambda) \cdot \bar{y}(\lambda))\Delta\lambda \qquad \text{(Eq. 18)}$$

$$Z = K_m \cdot \sum_{380}^{780} (R(\lambda) \cdot \bar{z}(\lambda))\Delta\lambda \qquad \text{(Eq. 19)}$$

3.4.3.1 (Continued):

where:

X, Y, and Z = tristimulus values
Y is in units of cd/m^2 is therefore luminance
K_m = maximum luminous efficiency (683 $lm \cdot W^{-1}$)
$R(\lambda)$ = measured radiance in watts per steradian and square meter
$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ = CIE 1931 Color matching functions
$\Delta\lambda$ = wavelength interval

CIE chromaticity coordinates are derived from the tristimulus values.

1931 coordinate system:

$$x = \frac{X}{X + Y + Z} \quad \text{(Eq. 20)}$$

$$y = \frac{Y}{X + Y + Z} \quad \text{(Eq. 21)}$$

1976 uniform color scale (UCS) system:

$$u' = \frac{4X}{X + 15Y + 3Z} \quad \text{(Eq. 22)}$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad \text{(Eq. 23)}$$

3.4.3.1.1 Wavelength Accuracy Verification:

3.4.3.1.1.1 Scope: This verification test will quickly check the wavelength accuracy of the spectroradiometer under suspicion. This simple test will look for specific mercury (Hg) spectral lines in the emission of a fluorescent lamp. Any fluorescent lamp should work for this test. This verification should be performed periodically or when there is suspicion of error in chromaticity.

3.4.3.1.1.2 Equipment:

1. Spot spectroradiometer under test.
2. Fluorescent lamp.
3. White reflective surface: white bond paper or poster board are good examples (no calibration required).

3.4.3.1.1.3 Setup:

1. Turn on the lamp and spectroradiometer system. Allow sufficient time to warm-up.
2. Place the white reflective surface in front of the spectroradiometer and focus on the surface of the reflector.
3. Illuminate the white reflector with the fluorescent lamp.

3.4.3.1.1.4 Procedure:

1. Take a measurement of the fluorescent light reflected from the white reflective surface.
2. Locate three spikes in the measured emission: they should be around 404 nm, 435 nm, and 546 nm. The exact locations of the Hg lines are 404.66, 435.84, and 546.07 nm.
3. Wavelength recalibration of the spectroradiometer is recommended if the location of the centroid of any one of the spikes is off by more than 1 nm.

3.4.3.1.2 Spectral Radiance Accuracy Verification:

3.4.3.1.2.1 Scope: This verification procedure will check the spectral radiance calibration of the spectroradiometer under suspicion because color (chromaticity) is computed from the measured spectral radiance. This verification should be performed monthly or when there is suspicion of error.

3.4.3.1.2.2 Equipment:

1. Spot spectroradiometer.
2. Spectral radiance standard.

3.4.3.1.2.3 Setup:

1. Perform a wavelength accuracy verification test prior to this test.
2. Turn on the spectroradiometer and allow sufficient time to warm-up
3. Position the radiance standard in front of the spectroradiometer. Allow sufficient time to warm-up the standard to the level provided in the certificate of calibration.
4. Align and focus the spectroradiometer on the measuring plane of the radiance standard.

3.4.3.1.2.4 Procedure:

1. Take a spectral reading of the radiance standard.
2. Compare the measured data to the radiance standard's certified data either spectrally or by integrated values.
3. If the measured data is off by more than 2% then spectral recalibration of the spectroradiometer is recommended.

3.4.3.2 Filter Colorimeter: A filter colorimeter measures tristimulus values directly by use of colored filters in the optical path of the detector. From these values the subject's chromaticity is computed.

3.4.3.2.1 Colorimetric Calibration Accuracy: The calibrated colorimeter's measured chromaticity (1931 CIE x,y) of a 2856 K color correlated source should be within 0.005 (x,y) of a lighting standard's certified values.

3.4.3.2.2 Colorimetric Calibration Accuracy Verification:

3.4.3.2.2.1 Scope: This verification will check the colorimeter's measured chromaticity by comparing the known chromaticity of a standard source to the measured values. Follow the manufacturer's guidelines for how often to perform this test or when there is a suspicion of error in the readings.

3.4.3.2.2.2 Equipment:

1. Filter Colorimeter.
2. Standard light source approximating CIE Standard Illuminant A.

3.4.3.2.2.3 Setup:

1. The colorimeter and lamp are assumed to be on and warmed up.
2. Focus the colorimeter on the measurement plane of the standard.

3.4.3.2.2.4 Procedure:

1. Measure the tristimulus values by selecting appropriate filters (e.g., Red, Blue, Photopic, and Xb). In four filter colorimeters, the X tristimulus value is equal to the Red reading plus the Xb reading.
2. Compute the 1931 CIE chromaticity from the following equations and compare the measured values to the known chromaticity of the standard.

$$x = \frac{X}{X + Y + Z} \qquad \text{(Eq. 24)}$$

$$y = \frac{Y}{X + Y + Z} \qquad \text{(Eq. 25)}$$

3. Recalibrate the colorimeter if the difference is off by more than 0.005 in either x or y.

3.4.3.2.3 Spectrally Induced Color Errors: Spectrally induced errors should not substantially contribute to the measurement errors for color.

3.4.3.2.4 Spectrally Induced Color Errors; Correction Factor Derivation:

3.4.3.2.4.1 Scope: The procedure will determine color correction factors for specific narrow band emissions that cause significant chromaticity errors. A set of tristimulus correction factors may have to be computed for each display color.

3.4.3.2.4.2 Equipment:

1. Filter Colorimeter
2. Spectroradiometer
3. UUT

3.4.3.2.4.3 Setup:

1. The display and test equipment are assumed to be on and warmed up.
2. Locate and mark a position on the display so that the spectroradiometer may be re-focused onto the same point.

3.4.3.2.4.4 Procedure:

1. Select a color (i) on the UUT.
2. Select an aperture similar in size and shape to an aperture in the spectroradiometer. The aperture should be large enough to preclude any spatial errors.
3. Focus the calibrated colorimeter to the specified position on the display.
4. Measure the tristimulus values (X_{Ci}, Y_{Ci}, Z_{Ci}) with the colorimeter using the tristimulus filters built into the equipment.
5. Remove the colorimeter and replace with the spectroradiometer. Locate the mark position on the display and align and focus the spectroradiometer to that spot.
6. Measure the UUT with the spectroradiometer and record the tristimulus values (X_{Si}, Y_{Si}, Z_{Si}).

3.4.3.2.4.4 (Continued):

7. Compute tristimulus correction factors for the colorimeter by dividing the spectroradiometer's tristimulus readings by the colorimeter's tristimulus readings for the same color as shown in following equations.

$$C_{X_i} = \frac{X_{S_i}}{Y_{S_i}} \times \frac{Y_{C_i}}{X_{C_i}} \quad \text{(Eq. 26)}$$

$$C_{Y_i} = \frac{Y_{C_i}}{Y_{S_i}} = 1.0 \quad \text{(Eq. 27)}$$

$$C_{Z_i} = \frac{Z_{S_i}}{Y_{S_i}} \times \frac{Y_{C_i}}{Z_{C_i}} \quad \text{(Eq. 28)}$$

8. To apply the correction factors, multiply the colorimeter's tristimulus reading by the color correction factor for the appropriate tristimulus value prior to computing chromaticity.

Conoscopic Video Photometry Systems:

The use of a conoscopic video photometer is acceptable provided that the accuracy of the system, in comparison with classic techniques of color and luminance measurement, is known. Either a direct optical or Fourier transform interface is acceptable for the purpose of providing photometry as a function of display viewing angle.

The angular accuracy of these systems is known to be better than ±1° for angle reporting through the collector optics at conical angles to greater than 40°. The luminance accuracy should be better than 4% over its dynamic range.

Positioning Equipment:

Viewing Angles:

Non-polar display viewing angles are defined from a line projecting normal to the display at the point of focus. These angles are symbolized by H and V for horizontal rotation and vertical rotation, respectively. Positive H angles are viewed from above and positive V angles are viewed from the right.

Spherical viewing angles, θ and ϕ, are angles measured from the "normal" and the "East" direction, respectively. The angle θ measures the tilt away from the "normal" in any direction while the angle ϕ specifies the viewing direction (i.e., 0°=West, 90°=North, 180°=East, and 270°=South).

3.4.3.2.4.4 (Continued):

The machine angles of the positioning equipment do not necessarily match those of the viewing angles described above and care should be made to identify the type of goniometer that is being used. For the non-polar viewing angles, H is the same as the horizontal rotation in a Type A goniometer and V is the same as the vertical rotation in a Type B goniometer.

3.4.4 Translational:

3.4.4.1 Positional Accuracy: The positioner should be repeatable and be capable of moving the display or measuring device in any direction to within 0.25 mm (0.01 in).

3.4.4.2 X-Y Positioner Orientation: The X-Y plane is assumed to be the plane of the display face with the positive X direction horizontal and to the right and the positive Y direction vertical and up. The positive Z axis is in the focus direction toward the measuring device. This is normally thought of as a right-handed coordinate system.

3.4.5 Rotational: A positioner that involves a rotation about one or more primary orthogonal axes is called a goniometer. There are three types of goniometers in use in the display industry (Type A, Type B, and Spherical). No system is claimed as a standard. However, the Type B system is widely used for display work because inherent in its design, it reduces cantilevered loads on the rotation stages. The rotational positioner is normally mounted atop a translational positioner that is used to re-position the UUT to the focal point of the detector. The types of goniometers below translate and rotate the UUT and not the detector. Positioners/goniometers that carry the detector are mathematically opposite and thus have their conversion equations swapped (Type A becomes Type B and vice versa).

3.4.5.1 Rotational Accuracy: The positioner should be capable of rotating the display or measuring device to within 1° on any axis.

3.4.5.2 Goniometer: Goniometers have two or three rotation stages and are described by their configuration as in Type A and Type B systems. The Type A and Type B goniometers are also known as North Polar and East Polar positioners, respectively. These designations describe the longitudinal and latitudinal nature of axes' geometry.

3.4.5.2.1 Type A, (I.E.S. designation): Figure 3 shows the axis orientation of a Type A goniometer. The UUT is mounted indirectly to a horizontal axis, rotation stage. In this configuration the horizontal rotation is dependent on the vertical rotation angle since its base of rotation is directly from the vertical rotation axis. The vertical rotation is measured from the display normal about the x axis or in the y-z plane as is shown in Figure 4, while the horizontal rotation is measured in the x-z' plane.

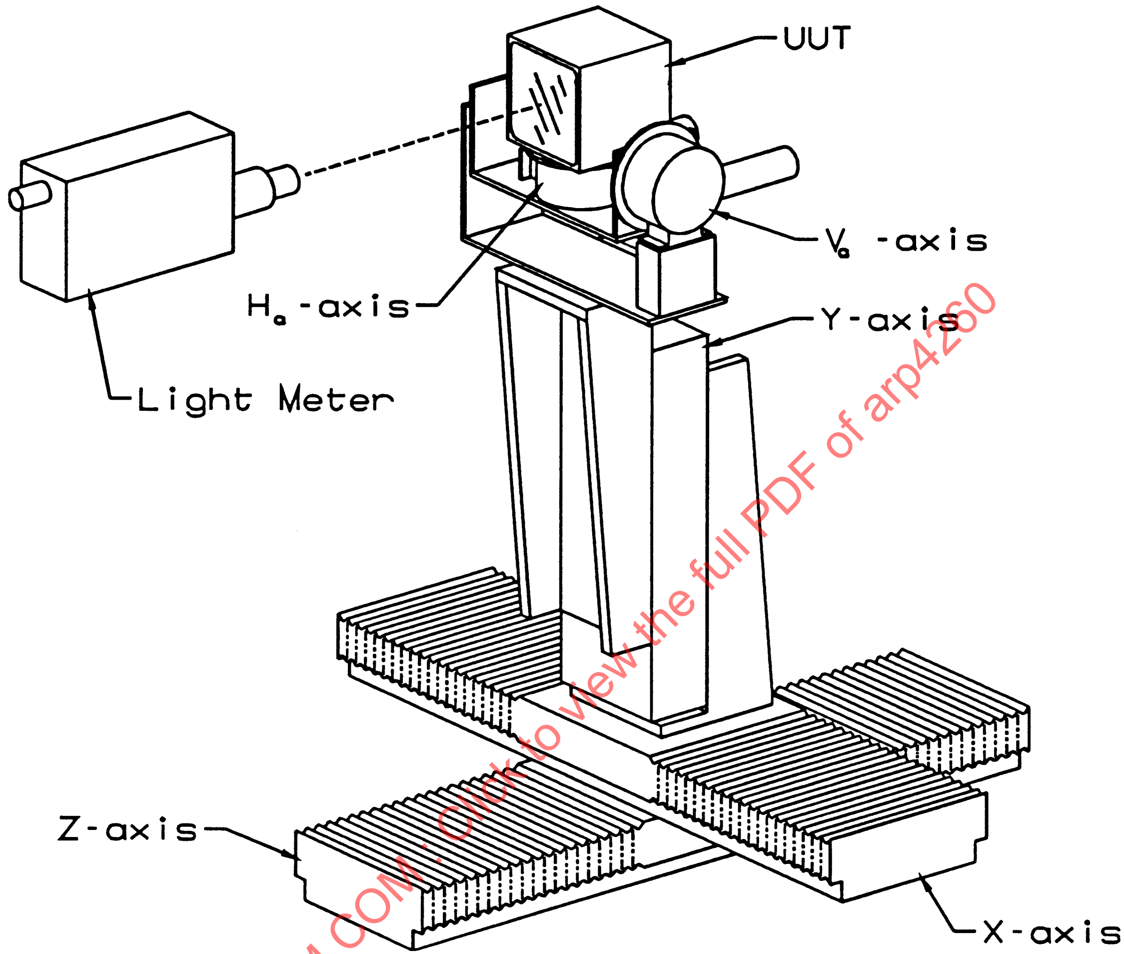

FIGURE 3 - Type A Goniometer

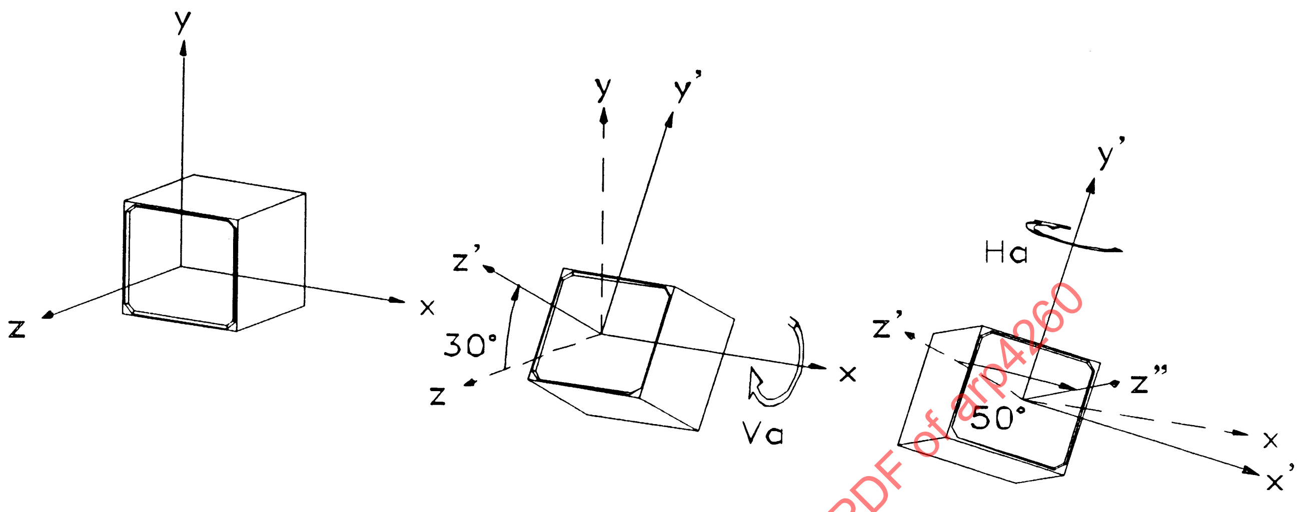

FIGURE 4 - Type A Axis Rotations

3.4.5.2.2 Type B, (I.E.S. designation): Figure 5 shows the axis orientation of a Type B goniometer. The UUT is mounted indirectly to a vertical axis, rotation stage. In this configuration the vertical rotation is dependent on the horizontal rotation angle since its base of rotation is directly from the horizontal rotation axis. The horizontal rotation is about the y axis or in the x-z plane as is shown in Figure 6 while the vertical rotation is measured in the y-z' plane or about the x' axis.

3.4.5.2.3 Spherical/Polar: In the spherical or polar rotational system the azimuthal rotation, ϕ, is around or about the display normal and the elevation, θ, (or zenith) rotation is away from the display normal in the direction of the azimuth position. An illustration of a typical system is shown in Figure 7 and the graphical rotations shown in Figure 8. This viewing angle coordinate system is used mostly by display vendors to describe the contrast performance of their displays. There appear to be two azimuth orientations in the industry: one has 0° location in the East position of a compass (along the x-axis of the display) and the other has the 0° location pointing north.

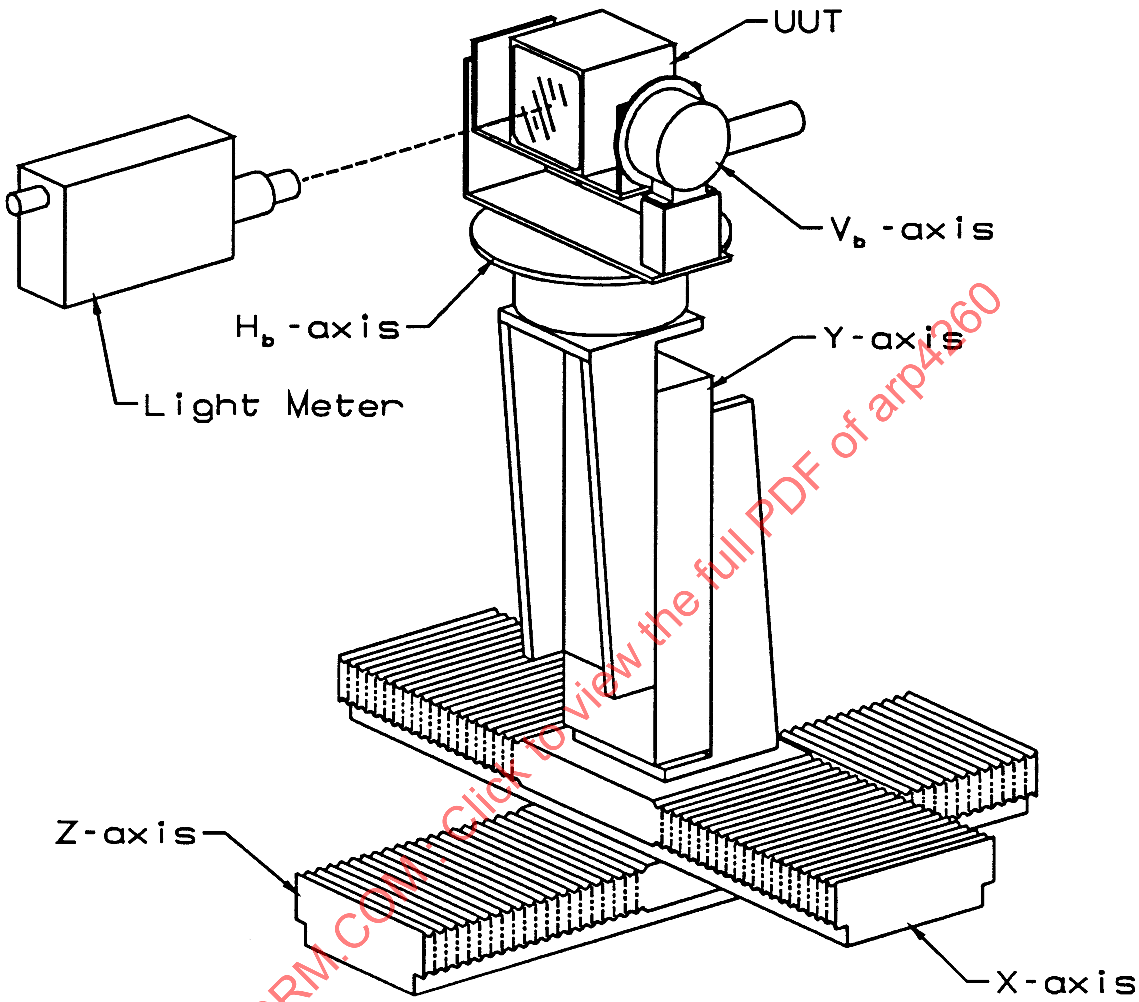

FIGURE 5 - Type B Goniometer

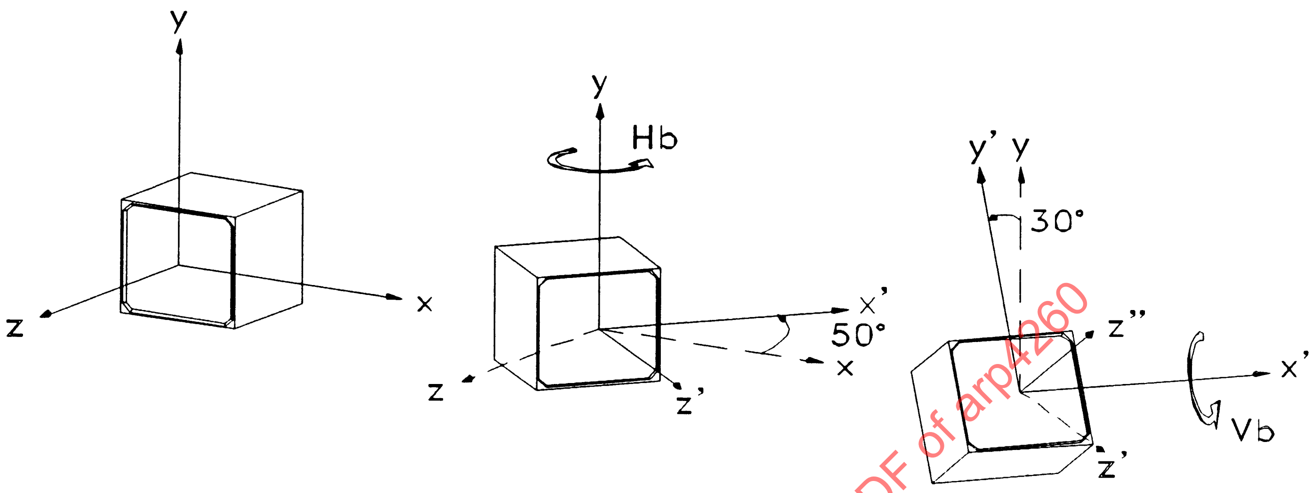

FIGURE 6 - Type B Axis Rotations

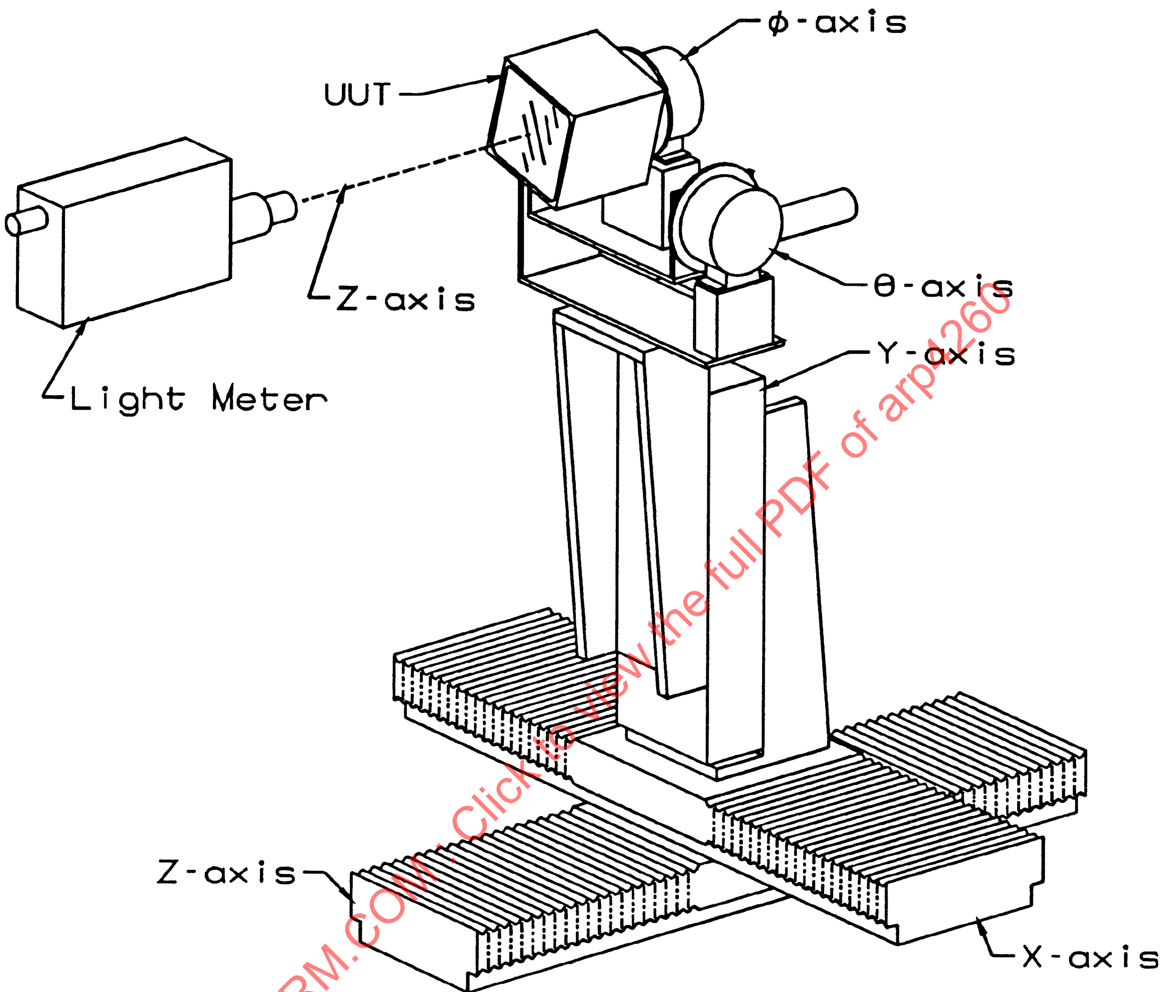

FIGURE 7 - Spherical Goniometer

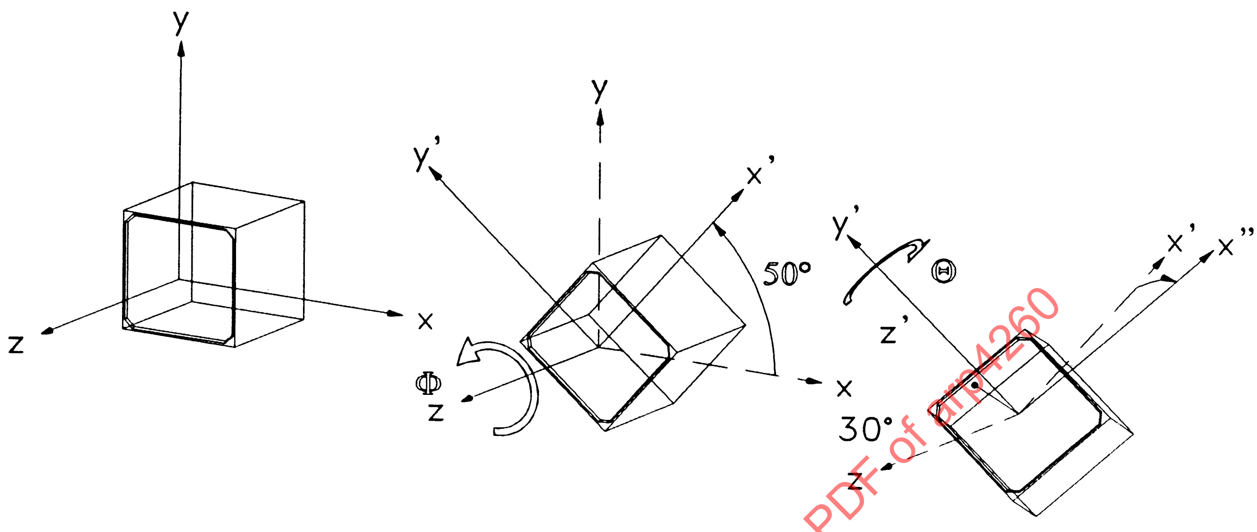

FIGURE 8 - Polar Axis Rotations

3.4.5.3 Coordinate Translation:

3.4.5.3.1 Type A to Type B Goniometer: To convert from Type A to Type B coordinates use the following relationships.

$$H_B = \arcsin(\sin H_A \times \cos V_A) \quad \text{(Eq. 29)}$$

$$V_B = \arctan\left(\frac{\tan V_A}{\cos H_A}\right) \quad \text{(Eq. 30)}$$

$$H_A = \arctan\left(\frac{\tan H_B}{\cos V_B}\right) \quad \text{(Eq. 31)}$$

$$V_A = \arcsin(\cos H_B \times \sin V_B) \quad \text{(Eq. 32)}$$

3.4.5.3.2 Type A/B to Spherical/Polar Goniometer: To convert from Types A or B to spherical coordinate system use the following relations.

To convert between Type A and spherical coordinates use the following equations:

To convert between Type B and spherical coordinates use the following equations:

$$\theta = \arccos(\cos H_A \times \cos V_A) \quad \text{(Eq. 33)}$$

$$\phi = \arctan\left(\frac{\tan V_A}{\sin H_A}\right) \quad \text{(Eq. 34)}$$

$$H_A = \arctan(\tan\theta \cos\phi) \quad \text{(Eq. 35)}$$

$$V_A = \arcsin(\sin\theta \sin\phi) \quad \text{(Eq. 36)}$$

To convert between Type B and spherical coordinates use the following equations:

$$\theta = \arccos(\cos H_B \times \cos V_B) \quad \text{(Eq. 37)}$$

$$\phi = \arctan\left(\frac{\sin V_B}{\tan H_B}\right) \quad \text{(Eq. 38)}$$

$$H_B = \arcsin(\sin\theta \cos\phi) \quad \text{(Eq. 39)}$$

$$V_B = \arctan(\tan\theta \sin\phi) \quad \text{(Eq. 40)}$$

3.5 Ancillary Equipment:

In this section, additional laboratory equipment is mentioned that may be useful in making light measurements. It is not the intention of this document to endorse any specific products.

3.5.1 Light Sources: The user should be aware that the lamp spectrum could affect the accuracy and results of a lighting measurement.

3.5.1.1 Arc Lamps:

1. A xenon arc or metal halide lamp may be used for high ambient illumination. The temporal stability of these lamps makes them not suitable for a lighting standard.
2. Arc lamps with quartz tubes may be used for solar simulation and weathering testing.

3.5.1.2 Integrating Spheres: In addition to other uses, integrating spheres may be used to supply a uniform diffuse source of light for reflectance measurements.

3.5.1.3 Incandescent Lamps:

1. Quartz halogen lamps are typically used for sunlight readability (contrast) measurements.
2. Incandescent lamps are used for spectral measurements where a continuous spectrum light source is needed.
3. A bright light source that is used for visual inspection would be an incandescent lamp used with a dichroic filter (hot mirror).

3.5.2 Optical Components:

1. An optical protractor is used to measure light incident angles and viewing angles.
2. A diffuse target for specular reflectance measurement is made of a white PTFE like material that has good spectral reflectance properties and near lambertian reflectance characteristics as well.
3. A hand-held illuminance meter similar to a photographer's f-stop meter is used to measure ambient illumination. It is very useful for setting high ambient illumination conditions for contrast measurements.
4. Inspection microscopes ranging form 5X to 200X are useful in testing matrix displays.

3.5.3 Mechanical Devices:

1. Vibration isolation table should be used where spatial stability is a important consideration when making lighting measurements. These conditions may be encountered when trying to measure inside a single display element.
2. Tripods are very useful in the lighting labs for holding ambient illumination lamps and photometers.
3. Miscellaneous clamps and holding fixtures are useful in the lighting lab.

4. MEASUREMENT PROCEDURES:

4.1 Important Measurement Considerations:

1. Laboratory conditions as described in 3.2 should be followed in these procedures unless specifically noted.
2. Unless otherwise specified, the measurements made in this document are performed normal to the display plane.
3. Most of the procedures are adaptable to Design Viewing Envelope (DVE) measurements for specific angles.
4. The UUT shall be sufficiently warmed up (stabilized) prior to making any measurements.
5. The measuring equipment shall be sufficiently warmed up (stabilized) and calibrated prior to making any measurements.
6. The display coordinate system is described such that the lower left corner of the display is 0,0 and positive X-directions are to the right and positive Y-directions are up.
7. Warning: Comparing a display's photometric data from instruments with different acceptance apertures can cause problems especially displays like twisted-nematic liquid crystal displays where the emitted polarization varies greatly with the angle from the display.

4.2 Multiple Point Measurement Positioning Guidelines:

4.2.1 Design Viewing Envelope Positioning:

1. For metrics evaluated over the DVE, it is recommended, for simplicity, to measure in the center of the display. This assumes that the center area is a good representative of the entire display.
2. It is recommended that the measured point is at or near the goniometer's center of rotation to minimize measurement error.
3. A typical angular step size for these measurements is 5° for engineering tests and 15° for production testing. The maximum angles stepped shall include the DVE maximums.
4. For better accuracy, perform all measurements at one angle and position before moving to the next (angle and position).
5. Rotating the display or photometer in any direction may cause a translation of the area of interest. Make sure to check the alignment and focus of the photometer following each rotational move.

4.2.1.1 Two Dimensional (Spatial) Positioning:

a. For these measurements, the display area will be divided into an X-Y grid.
b. An absolute minimum measurement grid size of 5 by 5 is recommended but is generally dependent upon the display size and customer's requirement.
c. The measuring area selected by either aperture size and/or distance should be large enough to preclude variations due to the display's pixel structure.

4.3 Luminance:

4.3.1 Area Luminance:

4.3.1.1 Scope: This is a basic procedure describing how to measure area luminance and will be referenced in other procedures in this document. The term “area” used here refers to the area of multiple pixels in the measuring field.

4.3.1.2 Equipment:

1. Spot photometer
2. Positioning equipment when multiple locations or viewing angles are required.

4.3.1.3 Setup:

1. The UUT will be set up to display a sufficiently large field (at least 25% greater than the largest aperture dimension) of the required colors. Allow the UUT to warm up.
2. The photometer shall be set up to measure an area such that the minimum dimension of the measuring aperture covers at least 10 pixels. The measuring aperture should be sufficiently large so that the ratio of the active to inactive element areas (and thus luminance) within the aperture becomes essentially constant.
3. Set up ambient lighting to illuminate the display surface (if required).

4.3.1.4 Procedure:

1. Select a field of color and luminance level to measure.
2. For each luminance reading, align and focus the photometer relative to the UUT at the locations and angles required.
3. Measure and record the area luminance. It is recommended to take several readings and compute the average of those readings.
4. Repeat steps 1 through 3 as needed.

4.3.2 Display Element Luminance:

4.3.2.1 Scope: This procedure describes how to measure the luminance of a single display element. The human eye does not discriminate individual display elements, so these measurements are not a direct measure of perceived brightness. Display element luminance varies greatly between display elements (due to cell spacers, color filters, etc.). A single display element luminance measurement shall not be used to characterize display luminance.

4.3.2.2 Equipment:

1. Positioning equipment
2. Spot photometer

4.3.2.3 Setup:

1. The UUT will be set up to display a field of the required color(s) and luminance level. Allow the UUT to warm up.
2. Select a measurement aperture whose largest dimension is 50 to 80% of the smallest dimension of one display element. The area measured by the photometer must lie completely inside the display element. Refer to Figure 2. This setup may require the use of special calibrations, lenses, and apertures of the photometer (see the photometer manufacturer's user manual).
3. Set up ambient lighting to illuminate the display surface (if required).

4.3.2.4 Procedure:

1. Align and focus the photometer so that the measuring aperture is centered within a single display element.
2. Measure and record the display element luminance. It is recommended to take several readings and compute the average of those readings.

4.3.3 Ambient Illumination:

4.3.3.1 Scope: This procedure describes a method to compute the ambient illumination, $I_{Ambient}$ incident on the display plane. Sources of ambient illumination might be sunlight simulation, room lighting, or undesired stray light.

4.3.3.2 Equipment:

1. Spot Photometer
2. Diffuse Reflectance Standard

4.3.3.3 Setup:

1. Align and focus the photometer on the display plane. The photometer’s optical axis is normal to the display.
2. Place the diffuse reflectance standard such that the reflecting surface of the standard is coplanar with the display plane.

4.3.3.4 Procedure:

1. With the ambient illumination incident on the standard, measure and record the luminance reading from the reflectance standard.
2. Compute the display's ambient illumination, in Step 1, on the diffuse reflectance standard by using the following equations. The result of the computation is illuminance because of the Lambertian characteristic of the diffuse reflectance standard. Be careful to use the correct conversion factors to match the units in use.

$$E_{Ambient} = \frac{L_{Diffuse\ Standard}}{\rho_{Diffuse\ Standard}} \qquad \text{(Eq. 41)}$$

where:

$L_{Diffuse\ Standard}$ = luminance on the diffuse standard
$\rho_{Diffuse\ Standard}$ = reflectance of the standard

4.3.4 Luminance Uniformity:

4.3.4.1 Scope: This procedure describes how to measure luminance uniformity.

4.3.4.2 Equipment:

1. Positioning equipment
2. Spot photometer

4.3.4.3 Setup:

1. The display UUT shall display a full field of the required color, gray scale, and luminance.
2. Set up ambient lighting to illuminate the display surface (if required).
3. For these measurements, the display area will be divided into an X-Y grid. A minimum grid size of 5 points by 5 points is recommended but is generally dependent upon the display size and customer requirements. If non-uniformities are visible, select a sufficient grid size or resolution to include these non-uniformities.
4. The aperture size is selected such that the smallest grid spacing is larger than the major aperture dimension. Refer to 4.3.1.3, #2 for minimum aperture.

4.3.4.4 Procedure:

1. Measure luminance at each grid location and record the data.
2. Perform necessary calculations as described in the next section where LMax is the measured maximum luminance and LMin is the minimum luminance measured.

4.3.4.5 Calculations:

4.3.4.5.1 Method 1:

$$\text{Luminance Uniformity (LU)} = \frac{L_{Max}}{L_{Min}} \quad \text{(Eq. 42)}$$

4.3.4.5.2 Method 2:

$$LU = \frac{(L_{Max} - L_{Min})}{(L_{Max} + L_{Min})} \quad \text{(Eq. 43)}$$

4.3.4.5.3 Method 3:

$$LU = \frac{(L_{Max} - L_{Min})}{L_{Avg}} \quad \text{(Eq. 44)}$$

where:

L_{Avg} = average luminance of the UUT

4.3.5 Contrast:

4.3.5.1 Scope: This describes the step by step procedure for measuring the display's contrast or contrast ratio. These parameters are measured under dark or high ambient conditions.

4.3.5.2 Equipment:

1. Spot photometer
2. High ambient illumination source as per 3.6.1, if required.

4.3.5.3 Procedure: Either of the two methods described below are suitable.

4.3.5.3.1 Same Point Method:

1. Align the photometer to a predefined position on the display.
2. Command the display to go to a white field in the predefined position and measure the luminance, L_W, of the white field.
3. Command the display to go to a black field in the predefined position and measure the luminance, L_B, of the black field.

4.3.5.3.2 Adjacent Point Method:

1. The UUT shall display adjacent white (L_W or foreground luminance) and black fields (L_B or background luminance) flat fields.

   NOTE 1: Unless otherwise specified, “White” and “Black” refer to the maximum and minimum gray scale settings for any color falling within the color gamut of the UUT.

   NOTE 2: This method is preferred for segmented displays. The white field refers to the activated segment and the black field refers to the adjacent background.

2. Align the photometer on the white field. Measure the luminance, L_W, of the white field.

3. Focus the photometer on the black field. Measure the luminance, L_B, of the black field.

4.3.5.4 Variables and Definitions:

$L_R \equiv$ the diffuse legend luminance as measured normal to the display under the specified incident illumination with the display commanded to its lowest gray scale and the backlight set to minimum. This is the reflected luminance with the display OFF. “R” refers to reflected light.

$L_{Ei} \equiv$ the specified gray scale “i” emissive legend luminance measured in dark ambient conditions at the FEP with the backlight set to the appropriate level for that viewing angle. “E” refers to emissive light.

$L_W \equiv$ the white display luminance measured in the specified high ambient conditions. This value is a superposition of L_R and L_{E7}: $L_W=L_R+L_{E7}$. L_{E7} is usually the brightest gray scale value in an three bit system.

$L_B \equiv$ the background (“B” is for background) is a superposition of the reflected ambient illumination and the display luminance in the lowest gray scale: $L_B=L_R+L_{E0}$.

4.3.5.5 Procedure for High Ambient Contrast: Contrast is computed from the display and background luminances which are described in the previous section.

$$\text{Contrast ratio} = CR = \frac{L_W}{L_B} \qquad \text{(Eq. 45)}$$

$$\text{Contrast} = \frac{L_W - L_B}{L_B} = CR - 1 \qquad \text{(Eq. 46)}$$

4.3.6 Reflectance:

4.3.6.1 Scope: This section contains procedures for acquiring data to evaluate the specular and diffuse reflectance. For simplicity, the data in these procedures is assumed to be taken photopically rather than spectrally.

NOTE: When switching between the UUT and the reflectance standard measurements in the following procedures, do not readjust the light source or photometer. In both test procedures no power is applied to the UUT because these are tests of reflectivity and not contrast.

4.3.6.2 Specular Reflectance:

4.3.6.2.1 Scope: Specular reflectance for displays occurs when light from a specific source, such as a white cloud, is incident upon the display face and is reflected to the viewer in a single (specular) direction like a mirror would reflect incident light. For an LCD, the specular reflection can consist of more than just the front surface of the cover glass. LCDs have other surfaces including polarizers, bus line connections in the liquid crystal cell, and other glass interfaces that can cause specular reflections. The sum of all these reflections make up the "total" specular reflection. This procedure covers multiple surface (or total) specular reflections.

4.3.6.2.2 Equipment:

1. An illuminated white diffuse target such as a white reflective surface or an integrating sphere. A stable, broadband light source capable of providing at least 1500 fc, with a color temperature approximating that of daylight should be used to illuminate the white target.
2. Spot photometer. The photometer's measurement aperture should be as large as possible, but smaller than the LCD and the reflected white image (minimum of 1/2 in as viewed on the LCD).
3. A specular reflectance standard (see 3.3.4.2).
4. A goniometer to locate the UUT at 30° to the photometer.

4.3.6.2.3 Setup:

1. The photometer, UUT (or reflectance standard), and white diffuse target should be set up as in Figure 9 or Figure 10. The angle, θ, between the normal of the test display and the incident light rays coming from the white diffuse target and display normal and the optical path of the photometer should be about 30°. The light path from the diffuse reflectance target to the UUT to the photometer lens lies on one plane; this plane should be horizontal to simplify the test. In Figure 9 the angle between the surface of the diffuse reflectance target and the depicted optical path ray to the specular reflectance standard should be close to 90°. This is done in order to reduce lambertian reflection errors. For the same reason the incident angle of the light source to the diffuse target should be greater than 60× from the surface of the diffuse target.
2. Turn on the light source. The light source is adjusted such that the illumination on the white diffuse target has no discernible hot spot; that is the ratio of the maximum to minimum luminance must be not greater than 1.5:1.
3. With the illuminated white diffuse target aligned with the test item (UUT or reflectance standard), the photometer is aligned so that the reflected image of the white diffuse target is in view and focused. The point of measurement should be at the center of the white diffuse target's image on both the reflectance standard and the UUT.
4. The largest dimension of the photometer's aperture should be less than one third of the white diffuse target's smallest dimension.
5. When using a reflectance target, care should be taken in the placement of the light source so that stray light is not directly incident in the photometer's optics. This can be done with careful lamp position and the use of light baffles.

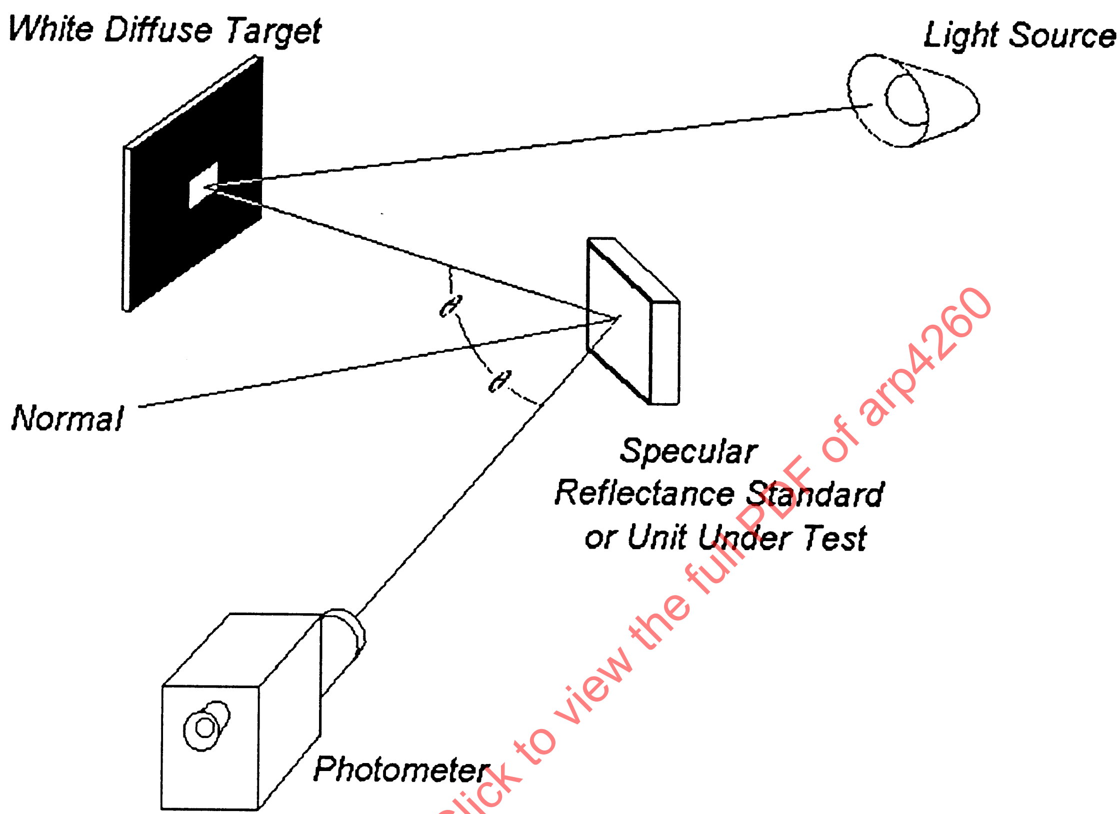

FIGURE 9 - Reflectance Setup

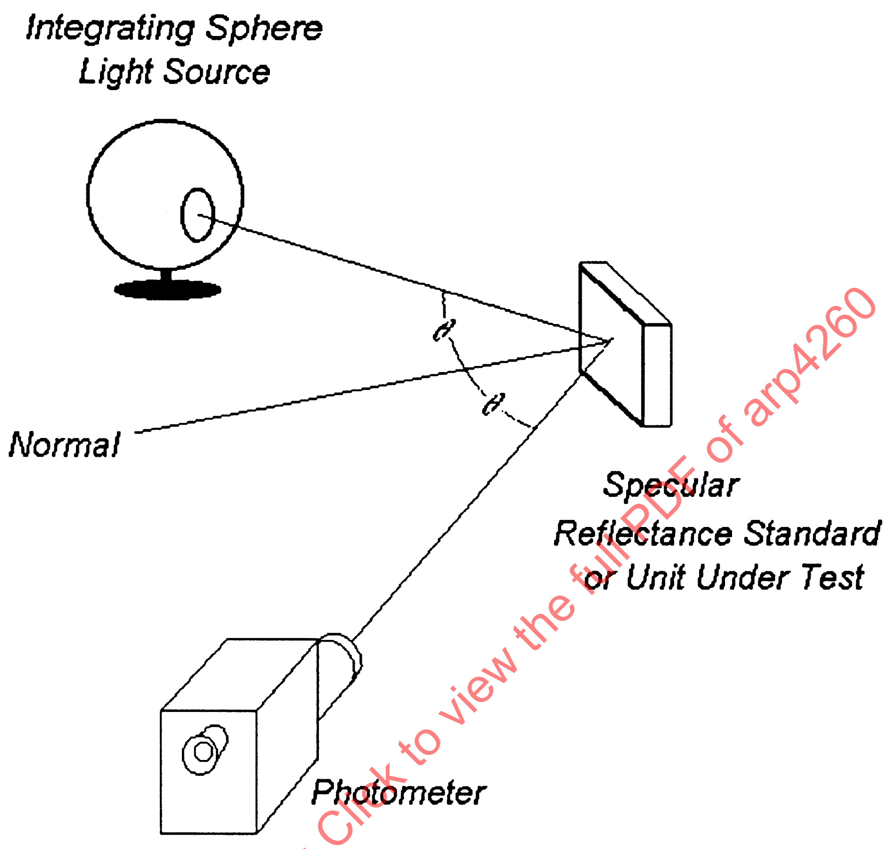

FIGURE 10 - Alternate Setup

4.3.6.2.4 Procedure:

1. Place the specular reflectance standard in the measuring position.
2. Measure and record the luminance, L_{SR}, of the white diffuse target by measuring the luminance of the reflected image. Calculate the luminance of the white diffuse target, L_S, from the known specular reflectance of the standard, ρ.

$$L^S = \frac{L_{SR}}{\rho} \quad \text{(Eq. 47)}$$

4.3.6.2.4 (Continued):

3. Remove the reflectance standard and replace it with the UUT. This is done by moving the display until the front surface of the display lies in the same plane as that of the reflectance standard. Make sure that power to the UUT is off. Now, while viewing through the photometer's optics, adjust the position of the UUT until the reflected image of the white diffuse target is the same as the reflectance standard. When viewing the display through the photometer, multiple reflected images may appear as illustrated in Figure 11. Position the display so the measuring aperture is totally inside the central brightest image comprising all of the reflections. It is at this point in the procedure that the aperture selection is verified correctly for at very large incident angles the overlapping image reflectance becomes small. The calibration procedure in Step 2 may have to be repeated.

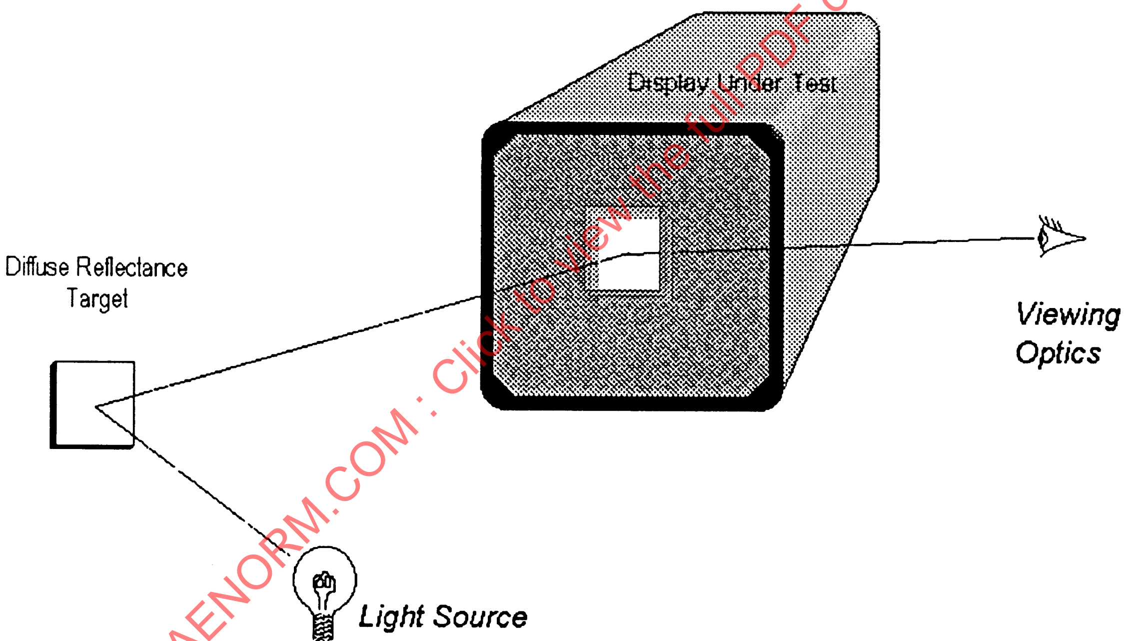

FIGURE 11 - Multiple Images

1. Record the luminance of the reflected image off of the UUT as LSUUT.
2. Calculate the total specular reflectance using Equation 48.

$$R_{UUT} = \frac{L_{SUUT}}{L_S} \qquad \text{(Eq. 48)}$$

4.3.6.3 Diffuse Reflectance Measurement:

4.3.6.3.1 Scope: This procedure defines how to measure diffuse reflectance which are all reflectances that are not specular. Diffuse reflectance degrades the readability in transmissive displays but it is utilized in reflective or transflective displays to enhance readability.

NOTE: This procedure attempts to reduce the effects of diffraction anomalies that occur when the incident illumination is aligned with pixel structures by moving the incident light out of alignment with these structures. The equipment setup is selected to minimize unwanted specular reflectances and to mimic the sun's orientation to the UUT. If other orientations (such as referenced in MIL-L-85762) can be proven equivalent they may be used in place of this.

4.3.6.3.2 Equipment:

1. Spot photometer
2. Diffuse reflectance standard
3. High intensity light source with a color temperature between 4500 and 6000 K.

4.3.6.3.3 Setup:

1. Position the light source as shown in Figure 12. Other angles may be required.
2. Position the photometer along the normal to the measurement plane.

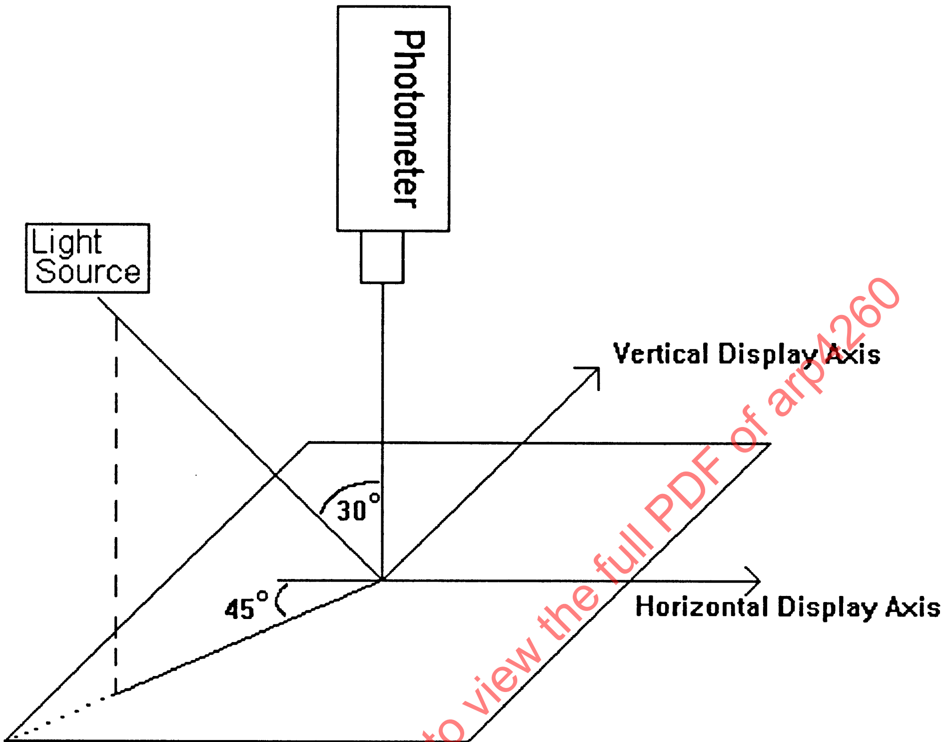

FIGURE 12 - Diffuse Reflectance Setup

4.3.6.3.4 Procedure:

a. Place the diffuse reflectance standard in the measurement position and focus the photometer on its surface.
b. Apply power to light source and adjust the illumination level to at least 2000 fc. Record the illumination level, L_{DR} after the lamp has stabilized.
c. The reflectance standard surface shall then be replaced by the display surface in the measurement plane by moving the display until it is focused in the photometer's optics. Measure and record the luminance, L_{DUUT}.
d. Compute the diffuse reflectance.

$$R_{UUT} = \frac{L_{DUUT}}{L_{DR}} \quad \text{(Eq. 49)}$$

4.3.7 Line Profile and Line Width:

4.3.7.1 Scope: This procedure measures the luminance profile of a straight line drawn at any angle (ϕ) on the UUT using a photometer's slit aperture. This aperture "looks at" less than two display elements in the direction of the measurement scan and multiple display elements along the length of the line. The resultant data from a single scan represents the spatial distribution of the line's luminance profile from which anti-aliasing algorithms may be evaluated or line width calculated. By repeatedly scanning the profile along the length of the line, the line luminance uniformity can be evaluated.

4.3.7.2 Equipment:

1. Photometer with slit aperture.
   a. The width of the measuring aperture should be less than half of the width of the line being measured but larger that the smallest dimension of a display element from the UUT.
   b. The length of the measuring aperture should be at least 5 times its width but less than ten times the smallest dimension of a display element from the UUT. (This minimum length to width ratio comes from product literature).
   c. In this procedure, the long (major) axis of the slit is assumed to be horizontal but is dependent on the individual photometer. The procedure should be adjusted accordingly depending on the orientation of the slit aperture. The angle ϕ is measured from horizontal with the positive direction in the counter-clockwise direction.
2. Goniometer (θ,ϕ,x,y,z)
   a. The ϕ axis is a rotation about the display "normal" and will be used to align the measuring slit aperture with the direction of the line drawn on the display.
   b. The same rotation cannot be achieved on the Type B goniometer but may be realized on the Type A goniometer by rotating the vertical axis, V_A, 90° and mounting the UUT such that the display and H_A axis are now aligned.
   c. An alternate arrangement for Types A and B goniometers would be to mount either the UUT or photometer in a goniometric cradle that could align the slit aperture with the line on the UUT.

4.3.7.3 Setup:

1. Mount the UUT on the goniometer, power up the unit, and allow the backlight to stabilize with some arbitrary pattern displayed on the UUT. The pattern should include a horizontal (ϕ=0°) line.
2. Select photometer's aperture and lens combination to achieve the required dimensions. Check this by aligning and focusing the photometer on a horizontal line.

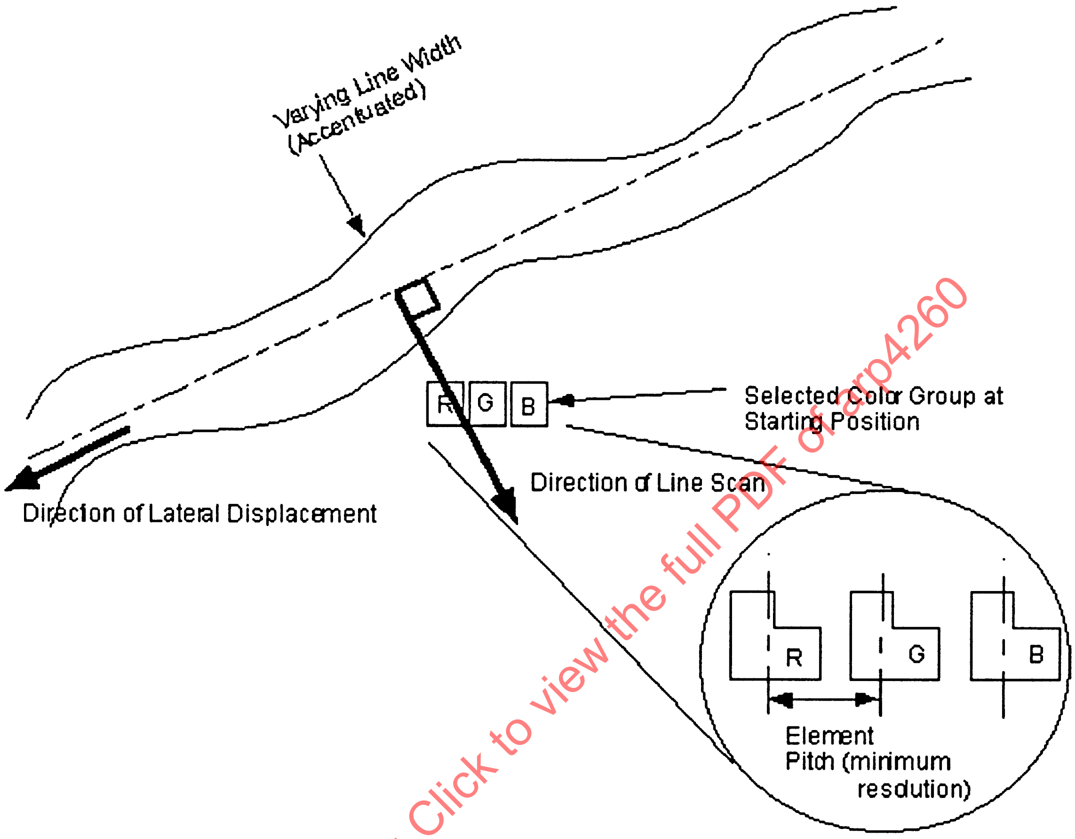

FIGURE 13 - Line Profile Setup

4.3.7.4 Procedure:

1. Draw a line, at ϕ degrees, on the UUT.
2. Position the measuring aperture on either side of but outside of the line to be measured. The direction of movement will be away from this initial position toward the opposite side of the line.
3. Measure luminance and distance the line (or photometer) is displaced.
4. Move the line or photometer the minimum step size that the line can be programmed to move.
5. Repeat steps 3 and 4 until the whole line has been scanned.
6. For line luminance uniformity reposition the measurement aperture along the length of the line a minimum distance equal to the length of the measurement slit and repeat steps 2 through 5. Continue to do this until a repeating pattern is obtained.

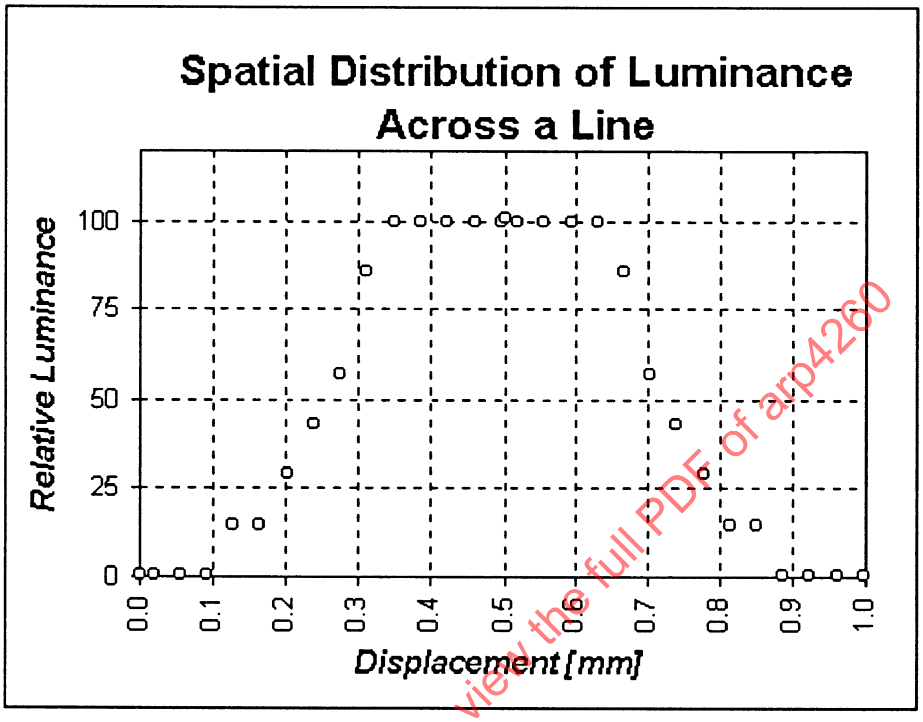

FIGURE 14 - Typical Line Profile Data

4.3.7.5 Analysis:

1. There are several methods for the analysis of the data. Typically the data is analyzed statistically for a fit to a desired profile or from the gray level and the line's angular position. Due to the many possible variations used for requirement verifications, details of specific analysis techniques are not provided. The analysis here will evaluate line width as defined by the 50% luminance point. Refer to Figure 15.
2. Line width is determined from an individual line profile data. Plot a luminance profile like that shown in Figure 14 from the data gathered in steps 1 through 7.
3. Connect the data points with straight line segments as shown in Figure 15.
4. Determine the 50% luminance level from the highest luminance measured in the profile and draw a line through the curve intersecting both slopes.
5. Extend vertical lines from the intersected slopes to the Displacement axis and note the positions (d_1, d_2) on the axis.
6. Calculate the line width as the difference between d_2 and d_1.

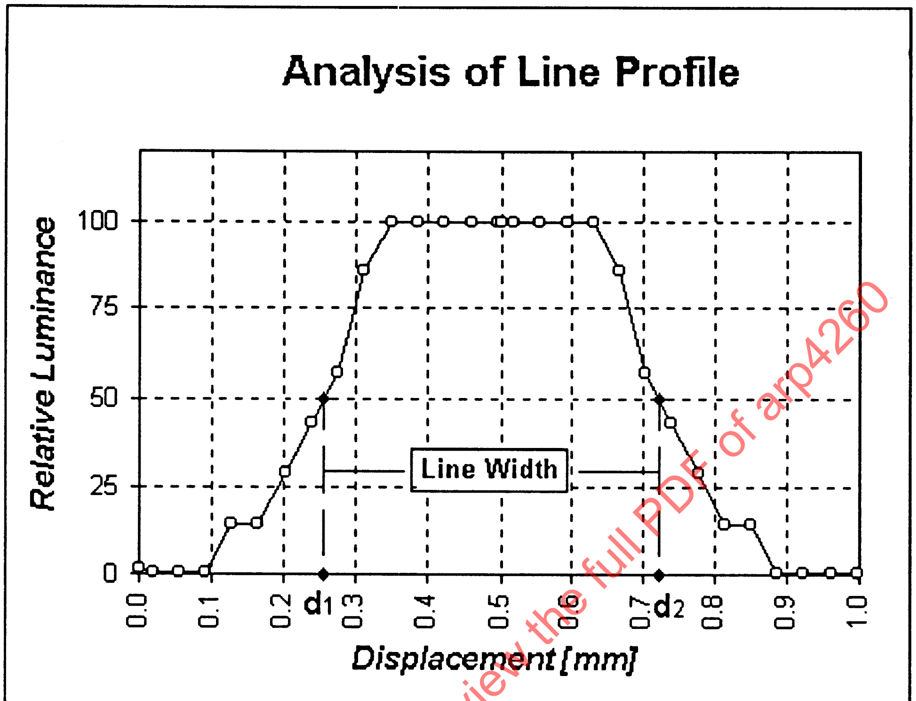

FIGURE 15 - Calculating Line Width

4.3.8 Crosstalk:

4.3.8.1 Scope: This procedure will visually test for cross coupling of electrical signals between elements of the display. This will provide an equation to compute a value for crosstalk and also give a quantitative value for crosstalk.

4.3.8.2 Equipment:

Photometer

4.3.8.3 Setup:

1. The test pattern described in Figure 16 needs to be generated and displayed over the entire active area on the UUT. The section marked B in this figure should be 5 to 10% of the display area and centrally located. This test should be performed in a dark room to aid in the detection of low level luminance differences.
2. The luminance of the UUT should be set to maximum for this test.
3. Binary (white/black) displays can only use Cases 1 and 3 (see Table 1). Gray scale capable displays should use a mid-level gray level in Cases 2 and 4. A mid-level gray level is one where the voltage at the element is tuned to approximately half of the maximum brightness.

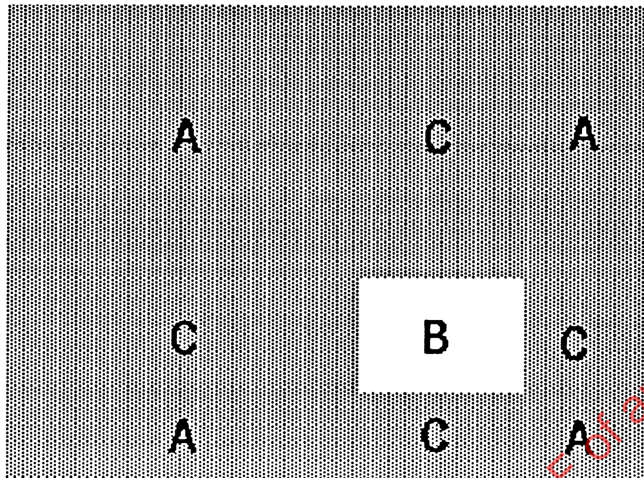

FIGURE 16 - Crosstalk Test Pattern

TABLE 1 - Crosstalk Setup Patterns

Case	Display Area A	Display Area B	Display Area C
1	“white”	“black”	“white”
2	“gray”	“black”	“gray”
3	“black”	“white”	“black”
4	“gray”	“white”	“gray”

4.3.8.4 Procedure:

1. Display the appropriate pattern described in Figure 16 on the display. Measure the display luminances in Display Areas A and C while staying within the Design Viewing Envelope.
2. If one or more of the regions marked “C” in Figure 17 is a different brightness than the regions marked “A”, then the display is said to exhibit crosstalk. Record the worst case measurement.
3. The percent crosstalk is calculated from the data collected in the preceding paragraphs and the following equation:

$$\%\text{Crosstalk} = \frac{|L_A - L_C|}{L_A + L_C} \times 100 \qquad \text{(Eq. 50)}$$

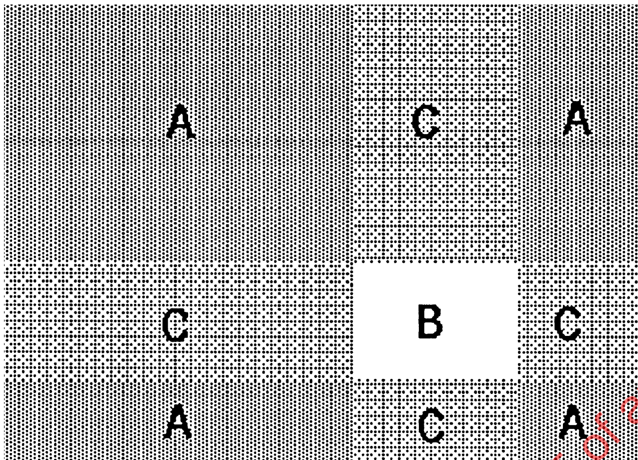

FIGURE 17 - UUT Showing Crosstalk

4.3.9 Gray Scale:

4.3.9.1 Scope: This procedure provides a method to measure gray scale performance over the DVE.

4.3.9.2 Equipment:

1. Spot photometer
2. Goniometric positioning equipment

4.3.9.3 Setup:

1. Align and focus the photometer to an area on the UUT having the desired gray scale level.
2. Allow the UUT's backlight to stabilize.

4.3.9.4 Procedure:

1. Move the UUT or the photometer to the initial measurement angle.
2. Command the area to be measured to a gray level.
3. Measure and record the area luminance of that gray level.
4. Repeat steps 2 and 3 for all gray levels of the primary colors.
5. If more viewing angles are required, move to the next measurement angle and repeat steps 2 through 4.
6. The data collected from the previous steps may be used to determine linearity and DVE gray scale performance.

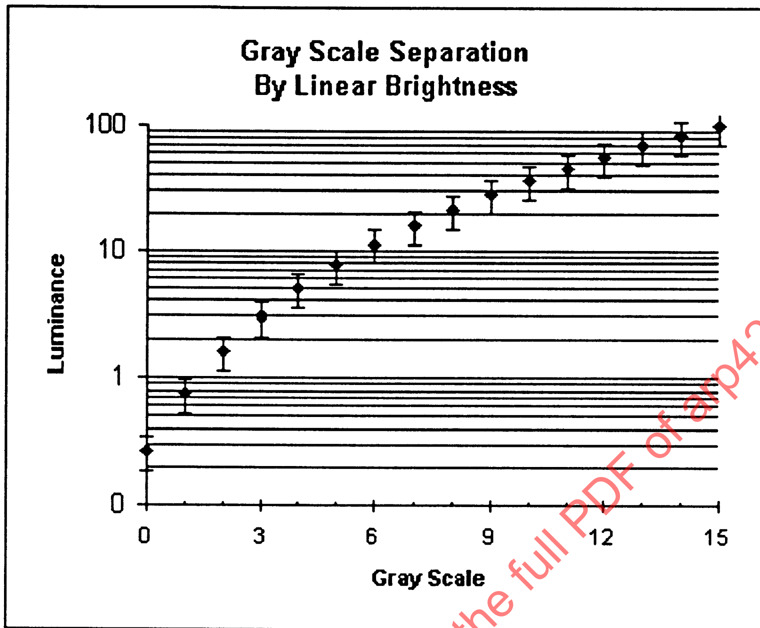

FIGURE 18 - Gray Scale Linearity

4.4 Color:

4.4.1 Spectroradiometric Measurements:

4.4.1.1 Scope: This procedure describes how to determine the chromaticity of a display by measuring its spectral distribution.

4.4.1.2 Equipment:

1. Spot spectroradiometer system (see 3.4.2.2)
2. Ambient illumination (see 4.3.3 if required).
3. Positioning equipment when multiple locations or angles are required.

4.4.1.3 Setup:

1. The UUT will be set up to display a sufficiently large field (at least 25% greater than the largest aperture dimension) of the required color(s). Allow the UUT to warm up and stabilize the color of the display.
2. The spectroradiometer shall be set up to measure an area such that the minimum dimension of the measuring aperture covers at least 10 pixels. The measuring aperture should be sufficiently large so that the ratio of the active to inactive element areas (and thus color) within the aperture becomes essentially constant.
3. Set up ambient lighting to illuminate the display surface (if required).

4.4.1.4 Procedure:

1. Select a field of color to measure.
2. For each color reading, align and focus the spectroradiometer relative to the UUT at the locations and angles required.
3. Measure and record the area color. It is recommended to take several readings and compute the average of those readings.
4. Repeat steps 1 through 3 as needed over the DVE.

4.4.2 Colorimeter Measurements:

4.4.2.1 Scope: This procedure describes how to determine the tristimulus values and color coordinates with a filter colorimeter.

4.4.2.2 Equipment:

1. Filter colorimeter. See equipment manufacturer for tristimulus calibration.
2. Ambient illumination (see 4.3.3 if required).
3. Positioning Equipment when multiple locations or angles are required.

4.4.2.3 Setup:

1. The UUT will be set up to display a sufficiently large field (at least 25% greater than the largest aperture dimension) of the required colors. Allow the UUT to warm up and stabilize the color of the display.
2. The spectroradiometer shall be set up to measure an area such that the minimum dimension of the measuring aperture covers at least 10 pixels. The measuring aperture should be sufficiently large so that the ratio of the active to inactive element areas (and thus color) within the aperture becomes essentially constant.
3. Set up ambient lighting to illuminate the display surface (if required).

4.4.2.4 Procedure:

1. Command the UUT to display the desired color.
2. Measure and record the colorimeter data that includes the luminance (Y). Some colorimeters automatically compute the chromaticity values (u',v') and display the results while with other colorimeters the chromaticity is computed from the measured and corrected tristimulus values (X,Y,Z) as shown in the equations. For more information on tristimulus values and chromaticity see references or 3.4.3.1.

$$u' = \frac{4X}{X + 15Y + 3Z} \quad \text{(Eq. 51)}$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad \text{(Eq. 52)}$$

4.4.3 Color Comparison Calculations:

4.4.3.1 Scope: There are several ways to quantify the difference between any two colors (in this case two color measurements) but only three methods will be described in this document. The parameters needed for the various color difference methods are Y_i, u'_i, and v'_i.

4.4.3.2 Procedure:

4.4.3.2.1 Total Color Difference, ΔE*: The total color difference equation (ΔE*) is used to compare any two colors by computing the distance between them in the three dimensional space (L*, u*, v*).

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}} \quad \text{(Eq. 53)}$$

where:

$$L^* = 116\left(\sqrt[3]{\frac{\text{Measured Luminance}}{Y_n}}\right) - 16 \quad \text{(Eq. 54)}$$

for measured luminances > 1 fL

$$L^* = 9.03 \times \text{Measured Luminance} \quad \text{(Eq. 55)}$$

for measured luminances < 1 fL

$$u^* = 13L^* (u' - u'_n) \quad \text{(Eq. 56)}$$

$$v^* = 13L^* (v' - v'_n) \quad \text{(Eq. 57)}$$

4.4.3.2.1 (Continued):

L^* = lightness of the measured color normalized to an object color stimulus (Y_n)

u^*, v^* = coordinates in the CIELUV uniform color space

u'_n, v'_n = chromaticity of the object color stimulus

CIE Illuminant D_{65} = generally used for the object color stimulus, if not otherwise specified in a requirements document Y_n = 100 in the units of luminance

Δu^* = difference between two measured u^* values

Δv^* = difference between two measured v^* values

4.4.3.2.2 Chroma, C*: The chroma equation is used to compare a measured color to object color stimulus (u'_n, v'_n). In some instances, colors are specified using chroma with u'_n, v'_n being the target chromaticity.

$$C^*_{uv} = 13L^* \left[(u' - u'_n)^2 + (v' - v'_n)^2 \right]^{1/2} \qquad \text{(Eq. 58)}$$

4.4.3.2.3 Chroma Difference, ΔC^*: The chroma difference equation is used to compare two colors that are supposedly identical. Chroma difference is often used in specifying color uniformity.

$$\Delta C^* = \sqrt{\Delta u^{*2} + \Delta v^{*2}} \qquad \text{(Eq. 59)}$$

4.5 Temporal:

4.5.1 Response Time:

4.5.1.1 Scope: This section describes two methods to evaluate the temporal response of a display. One is the integration method (specified in ARP4256) and the other is the10 to 90% method (a more general technique used in the commercial display industry). Both methods use essentially the same test equipment, setup, and data gathering procedure but differ in the data reduction and analysis.

The display's response time is dependent on its temperature. Therefore, the display temperature should be recorded with the data.

4.5.1.2 Equipment:

1. A photo detector (or photometer). The detector must have a spectral response limited to the visible range. The acceptance angle of the detector should be 3° or less. The detector should have an electro-optic response faster than $t_u/(4N)$ where t_u is the update period and N is the number of data points (minimum of 10). Therefore, the minimum response time of the detector is $t_u/40$.
2. Storage oscilloscope or an acquisition system capable of storing digitized waveforms displaying voltage versus time.

4.5.1.3 Setup:

1. Definitions:
   L_c = commanded display luminance
   L_{t0} = initial display luminance
   $L_{(t)}$ = display luminance as a function of time after command to change luminance.
   t_0 = start of the update period
   t_u = data update period
2. The UUT and test equipment is assumed to be on and warmed up.
3. Focus the photometer or place the photo detector on the display to be measured. This measurement is made normal to the display. The area measured should be small (<10 pixels) to reduce scatter.
4. Connect the analog output from the photodetector (or photometer video output) to the vertical input of the oscilloscope and adjust the vertical gain and the timebase controls to obtain a stationary waveform similar to the one shown in Figure 19. (The waveform shown is for a single event and will vary for different display temperatures.)
5. Adjust the vertical position so that the luminance equates to the “0%” level on the oscilloscope’s display. The t_0 luminance level (L_{t0}) must be determined by commanding the UUT to the L_{t0} level.
6. Set the display to L_c. Adjust the vertical gain of the oscilloscope so the steady state luminance equates to the “100%” level on the oscilloscope’s display.
7. Repeating steps 5 and 6 may be required to obtain the proper oscilloscope display for calculation.
8. Adjust the direction and sensitivity of the trigger such that a very small change in luminance triggers a trace on the oscilloscope. As an alternative, an external trigger to the oscilloscope may be used: one that is applied when the display under test changes data.

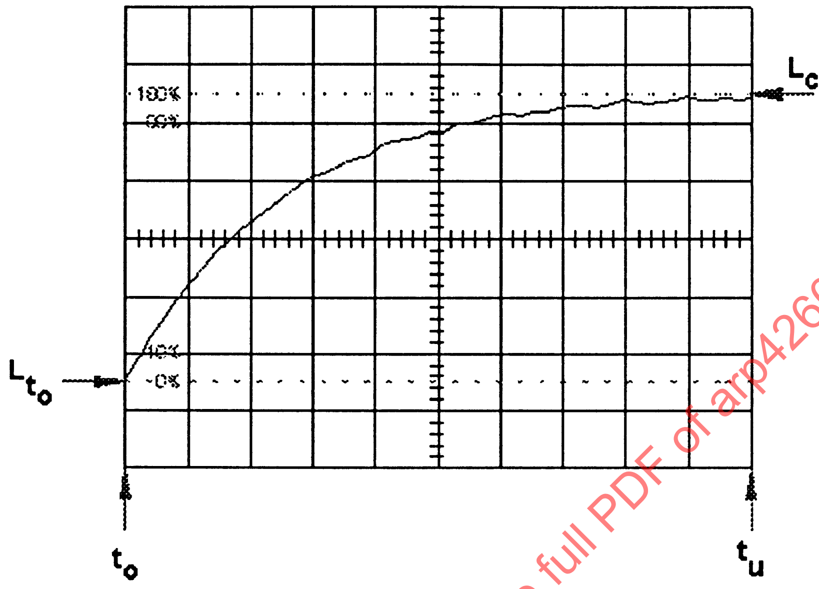

FIGURE 19 - Off to On Response Time ($L_c > L_{t0}$)

4.5.1.4 Procedures: This section shows a lack of detail in the procedures because of the variation in oscilloscope and digitizer controls.

4.5.1.4.1 Data Collection: Response time data should be collected for both the Off to On and On to Off states because there could be a large difference between the two parameters depending upon the type of display and operating temperature of the UUT.

4.5.1.4.1.1 Off State to On State:

1. For collecting the data, the recommended technique is to have the display driver toggle between commanded L_{t0} and L_c at rate of $(10t_u)^{-1}$ Hz. The rate should be slow enough so that the display can reach the commanded luminance.
2. While the driver is free-running as described in step 1, select a positive trigger to capture the L_{t0} to L_c part of the waveform. See Figure 19, where $L_c > L_{t0}$.

4.5.1.4.1.2 On State to Off State:

1. For collecting the data, the recommended technique is to have the display driver toggle between commanded L_{t0} and L_c at rate of $(10t_u)^{-1}$ Hz. The rate should be slow enough so that the display can reach the commanded luminance.
2. While the driver is free-running as described in step 1 then select a negative trigger to capture the L_{t0} to L_c part of the waveform. See Figure 20, where $L_{t0} > L_c$.